

Mechanical properties of information papers: the effect of adding softwood kraft pulp

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ADDITION OF SOFTWOOD KRAFT pulp to a paper furnish improves the mechanical properties of the paper. The sheet's optical and, to some extent, its surface properties typically decline with an increasing proportion of softwood reinforcement pulp. The mechanical properties can be important during web processing. For example, in operations like coating and slitting, web runnability must be ensured. Pressroom operations and end-user convenience also make their demands on mechanical properties.

This work attempts to clarify how softwood kraft reinforcement pulp improves some mechanical properties of paper. The discussion also considers the effects of pulp beating and paper calendering on sheet mechanical properties.

With modern paper machinery, the mechanical properties of wet webs are usually not as critical as the dry-end demands. Thus this work concentrates on the mechanical properties of sheets with moisture content below 20%. Effective dewatering systems are usually needed to ensure even formation. The effect of softwood kraft pulp on the dewatering properties will not be discussed here.

Environmentally controlled factors such as moisture content and temperature affect the mechanical properties of paper. This work pays little attention to such extraneous factors, focusing exclusively on the effect of softwood reinforcement pulp. However, the discussion does

include environmental factors and processes that directly affect the performance of the reinforcement pulp.

The mechanical properties considered in this study are:

- Tensile stiffness
- Bending stiffness
- Tensile strength
- Rupture strain
- Fracture energy.

In addition, dimensional stability with changing moisture content is briefly discussed. The intent is to analyze *how* reinforcement pulp contributes to each of these properties by exploring some theoretical and phenomenological issues. The hypothesized effects are then demonstrated with experimental observations, mainly from laboratory-scale experiments where both pressure groundwood and hardwood kraft pulp were reinforced with four different softwood kraft pulps.

TENSILE STIFFNESS

The seminal paper by Cox (1) and later works of Page and Seth (2, 3) proposed that the Young's modulus of a sheet made of fibers could be expressed as

$$E = \frac{1}{3} E_f (1 - \phi) \quad (1)$$

where

E = Young's modulus of the paper

E_f = Young's modulus of a fiber

ϕ = a parameter describing the inefficiency of stress transfer between

PAPER STRENGTH

ABSTRACT

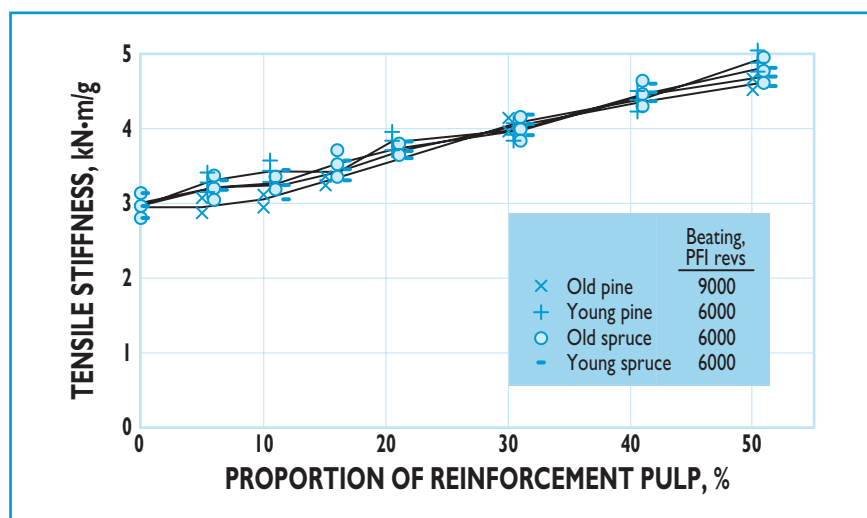
Reinforcing highly refined pressure groundwood with softwood kraft pulp increased tensile stiffness while decreasing bulk, so there was no net effect on bending stiffness. Tensile rupture strain increased, thus indicating that tensile strength index increases slightly more than tensile stiffness index. There was considerable nonlinearity in the tensile strength index of reinforced groundwood paper as a function of the proportion of reinforcement pulp, with small amounts of kraft pulp producing no increase in strength. Adding softwood kraft pulp to a hardwood kraft pulp had little effect on stiffness and strength. Addition of softwood kraft reinforcement pulp had a much greater effect on the fracture energy of paper than on tensile strength. Assuming that the fracture energy (or toughness) together with flaw size distribution determines the greatest load a paper web can carry, it may be feasible to evaluate softwood reinforcement pulps based on the fracture energy. The fracture energy of paper appears to be a linear function of the proportion of reinforcement pulp, suggesting that reinforcement pulps might be evaluated from pure kraft pulp handsheets.

Application:

Softwood kraft fiber reinforcement is effective in papermaking and converting operations where the fracture energy is a crucial material property. The effect of reinforcement on other mechanical properties seems much more moderate.

fibers, having a value of zero for very effective stress transfer and 1 for unbonded fibers.

Cox (1) further derived (a) how the prefactor 1/3 depends on fiber orientation distribution (this particular value being valid for random



I. Tensile stiffness index of groundwood paper as a function of the mass proportion of four chemical reinforcement pulps (pulp beaten to 40–50°SR; sheets calendered at 30 kN/m; 95% confidence limits are shown)

sheets only) and (b) how the stress-transfer inefficiency factor, ϕ , depends on the ratio of Young's and shear moduli of the fibers as well as the width-to-length ratio and relative bonded area of the fibers (2, 3). Bond stiffness also might be added to the factors contributing to the stress-transfer inefficiency factor, ϕ (4, 5).

Equation 1 proposes that in the case of well-bonded fibers, the tensile stiffness of paper depends on fiber stiffness, whereas in the case of poorly bonded fibers, stress-transfer efficiency can have a considerable effect on paper stiffness. The effective fiber modulus and the stress-transfer efficiency can be affected by fiber shape (curl, crimps, and kinks) (6, 7).

Another approach to the tensile stiffness of a fibrous material can be introduced through percolation theory (8–13), "percolation" referring to a phenomenon where a group of objects forms a continuous network. A fibrous medium can carry load only in (apparent) densities above the critical density at which percolation occurs. In other words, with decreasing density, the mechanical properties reduce to zero when the density decreases to a critical nonzero value where a continuous network no longer exists.

The percolation theory proposes that slightly above the threshold, the properties of the network are proportional to

$$(\Gamma - \Gamma_c)^\beta$$

where

Γ = a connectivity parameter

Γ_c = the critical value of this parameter

β = a percolation exponent

Well above the percolation threshold, the Young's modulus of the paper should be more or less linearly proportional to bond density or the mass density of paper (12–14), and the Young's modulus of the paper should also be proportional to the modulus of the fibers. The value of the connectivity parameter, Γ , depends not only on the mass density of the network but also on the dimensions of the fibers (11,12,15,16).

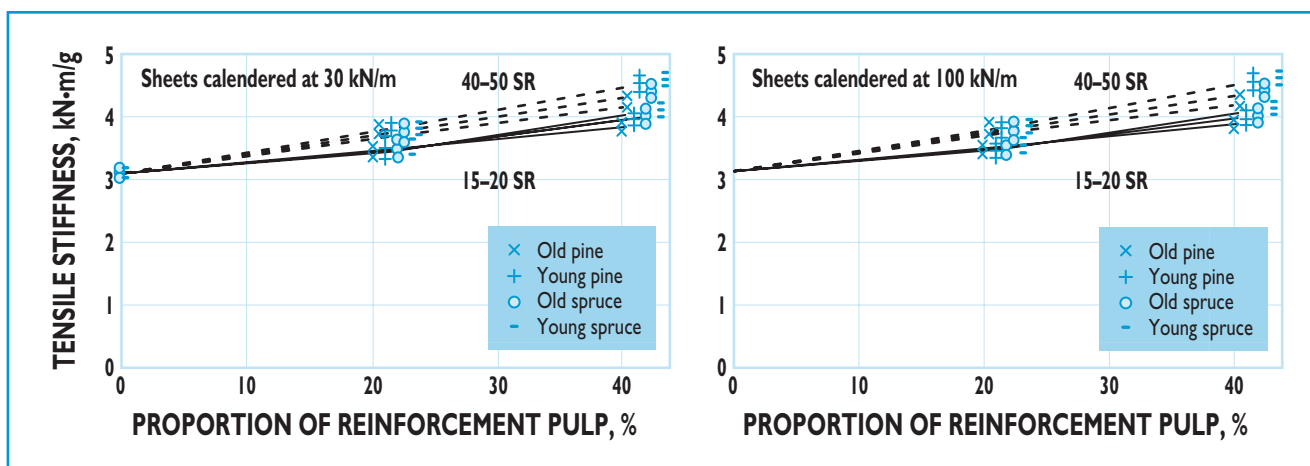
A percolation model and an effective-medium model like that given in Eq. 1 unify at high density. Both approaches agree that two factors are essential to understand the tensile stiffness of paper: fiber modulus and the efficiency of stress transfer between fibers, i.e., fiber modulus and fiber bonding.

Fiber modulus has been shown to depend on structure and chem-

istry. In the case of fibers with defects like microfibrillar dislocations, these dominate the mechanical properties (17). Defects do not necessarily have to be man-made: Pits in tracheid walls act as stress-enhancing flaws (18). On the other hand, the tensile stiffness of flaw-free fibers depends heavily on the orientation of the microfibrils, as demonstrated by theoretical and experimental treatments (17,19–22). Finally, in the case of flaw-free fibers with small microfibril angle, the fiber modulus depends on the chemical structure of the cell wall, with delignified fibers in the dry state probably being stiffer than mechanical fibers (20, 22–24).

Fiber bonding depends heavily on sheet structure, which is affected by the flexural rigidity of the fibers, which in turn depends on fiber morphology and the mechanical properties of the cell wall. Both are affected by mechanical and chemical treatments. Fiber bonding is also affected by other media surrounding the fibers, like fillers and fines. The surrounding media can act as bonding or debonding agents, depending on their character. Finally, fiber bonding depends on the physical and chemical structure of the fiber surface, being affected by numerous complex phenomena.

Another question is whether it is at all reasonable to describe paper as a network of fibers, as suggested previously. For example, a highly refined mechanical pulp may consist largely of small particles with high specific surface, which can induce appreciable cohesion. In such a case, it may be at least as reasonable to assume paper is a hydrogen-bonded homogeneous solid (25, 26) as it is to discuss it as a network of fibers. Alternatively, one can approach the mechanical properties of high-density papers using the composite laminar approach, where the mechanical properties are derived from the properties of each of the constituent



2. Tensile stiffness index of groundwood paper as a function of the mass proportion of four chemical reinforcement pulps at two levels of beating for lightly calendered sheets (left) and heavily calendered sheets (right) (95% confidence limits are shown)

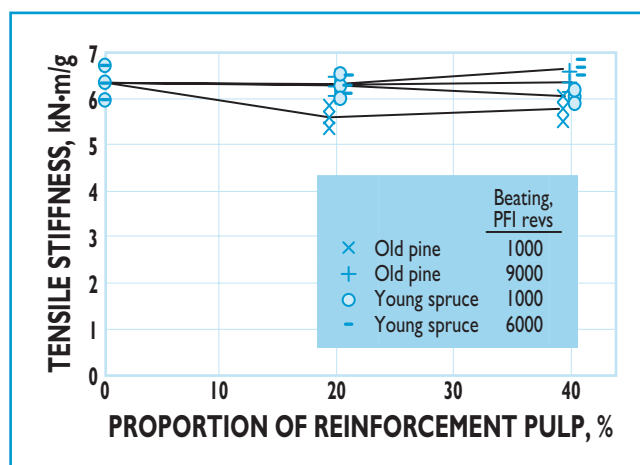
polymers rather than the properties of fibers or hydrogen bonds (27–29).

The effect of chemical softwood reinforcement pulp on the tensile stiffness of the paper may therefore depend considerably on the other furnish components. Let us consider three different cases:

- Case 1—reinforcement of a medium consisting of small particles with low cohesion
- Case 2—reinforcement of a medium consisting of small particles with high specific surface and appreciable cohesion
- Case 3—reinforcement of a medium of other kinds of fibers.

Case 1 could occur, for example, in papers with lots of mineral fillers. In this case, the number of contacts to be created between the reinforcement pulp fibers could significantly affect the mechanical properties of the paper, and it might be reasonable to discuss the connectivity of the reinforcement fiber network in terms of percolation theory. For Case 1, the expected result would be a considerable nonlinear increment in the tensile stiffness of the paper as a function of the proportion of the reinforcement pulp, the efficiency of which should depend on the ratio of fiber length to cell-wall thickness (11, 12, 16, 30).

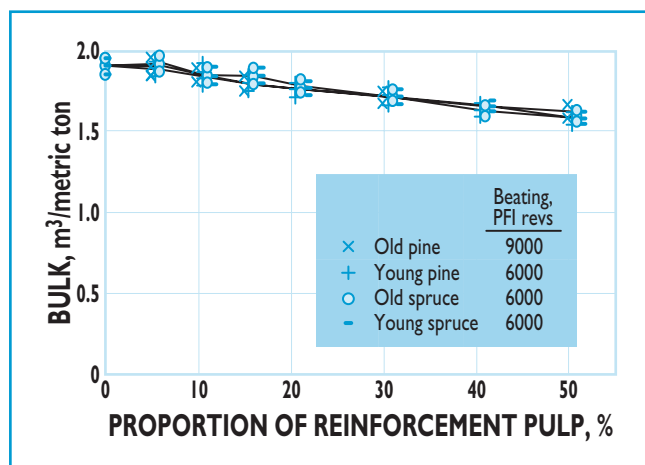
The higher the cohesion within the medium to be reinforced, the higher will be the tensile stiffness of the paper without reinforcement. Thus the increment in the tensile stiffness of the paper is not necessarily very pronounced as a function of the proportion of the reinforcement pulp. In low concentrations of reinforcement pulp, the bonds created between the particles of the medium to be reinforced may be at least as important as the bonds created between the reinforcement fibers. Moreover, if the bonding between the particles of the



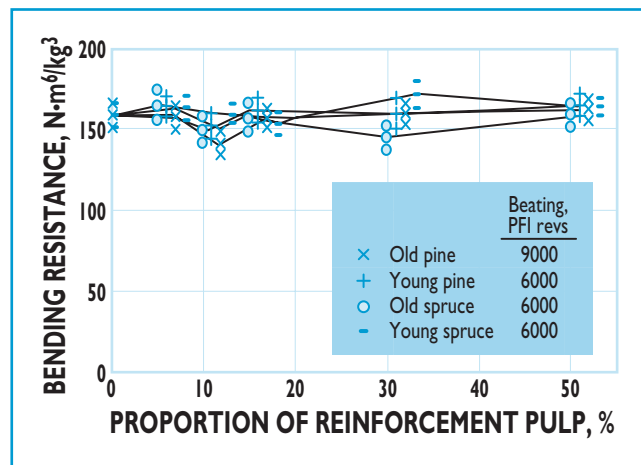
3. Tensile stiffness index of wood-free paper as a function of the mass proportion of two chemical reinforcement pulps at different levels of beating (sheets calendered at 30 kN/m; 95% confidence limits are shown)

medium and the reinforcement fibers is appreciable, the connectivity of the network of reinforcement pulp fibers does not dominate the mechanical behavior. Little or no nonlinearity of stiffness can be expected as a function of the proportion of reinforcement pulp, and arguments related to the connectivity of the network of reinforcement fibers provide little help in pulp evaluation.

With modern mechanical pulps, cases 2 or 3 may be more realistic scenarios than case 1. This is experimentally demonstrated in Fig. 1, where pressure groundwood (44 mL CSF) is reinforced with four different softwood kraft pulps. The results show that an increment in reinforcement pulp did increase the tensile stiffness index, although the original stiffness of the groundwood also was appreciable. There is some variation among the reinforcement pulps, but there is no apparent systematic percolation nonlinearity.



4. Bulk of groundwood paper as a function of the mass proportion of four chemical reinforcement pulps (pulps beaten to 40–50°SR; sheets calendered at 30 kN/m; 95% confidence limits are shown)



5. Bending resistance of groundwood paper as a function of the mass proportion of four chemical reinforcement pulps (pulps beaten to 40–50°SR; sheets calendered at 30 kN/m; 95% confidence limits are shown)

In Fig. 1, all the reinforcement pulps had been beaten to a dewatering resistance of 40–50°SR (Schopper-Riegler). The effect of pulp beating is shown in Fig. 2. The results show that extended beating of the reinforcement pulp in a PFI mill increased the stiffness, whereas heavy hard-nip calendering had a negligible effect. In terms of a network theory, we might argue that extended beating makes the stress transfer between fibers more effective; or we might claim that the paper approaches a dense continuum structure, where the properties are dominated by the properties of the cell-wall polymers.

It is obvious that calendering breaks bonds and causes fibers to deteriorate, but it also creates new contacts between particles, so the net effect is often only a moderate decrease in tensile stiffness (31–33).

A different kind of behavior was found when the reinforcement pulps were blended with a commercial hardwood kraft pulp, as seen in Fig. 3. Softwood reinforcement pulp did not increase the stiffness of the paper. In terms of the network theory, this implies that fiber length no longer essentially contributes to the stiffness of a high-density wood-free paper. Adopting the composite laminar approach, one might claim that

the mechanical stiffness of the cell-wall components do not differ markedly between the hardwood and softwood pulps. However, the situation of unaffected paper stiffness might change in a medium containing a considerable quantity of fillers with little cohesion.

BENDING STIFFNESS

The bending stiffness of an object can be expressed as the product of the Young's modulus of the material and the object's moment of inertia. The moment of inertia of a beam or a plate is proportional to the third power of the thickness of the plate. Indexing the in-plane tensile stiffness according to width and grammage rather than cross-sectional area yields a bending stiffness proportional to the product of tensile stiffness index and the square of the thickness.

Figure 4 shows the thickness of reinforced groundwood paper indexed according to grammage, i.e., sheet bulk, as a function of the mass proportion of chemical reinforcement pulp. The results show that the paper becomes somewhat denser with increased chemical pulp content. This means that the product of the tensile stiffness index and the square of bulk does not noticeably increase with the increment of soft-

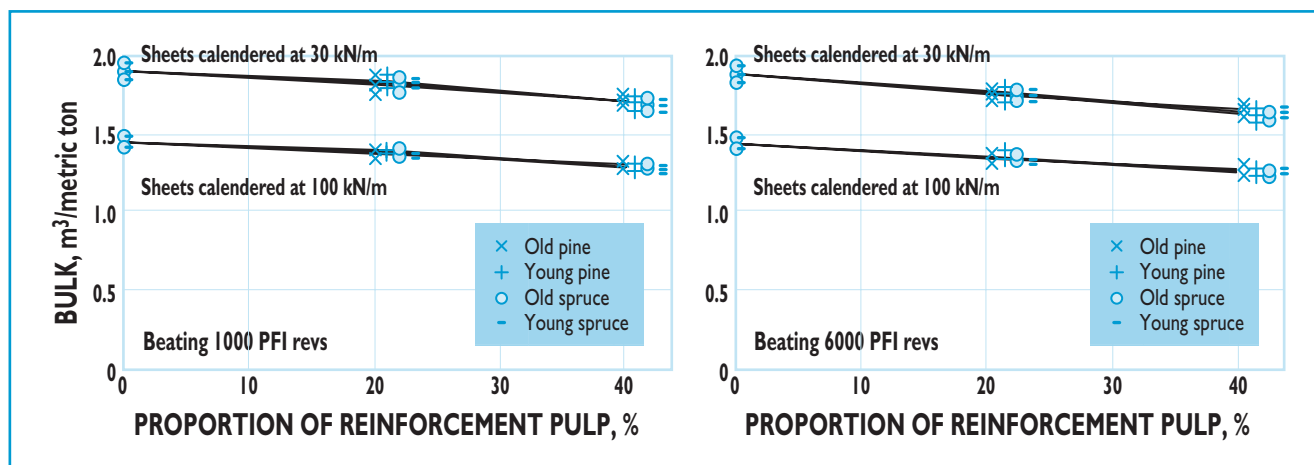
wood reinforcement pulp, even though the tensile stiffness index increases (Fig. 1). The same unresponsiveness to reinforcement is seen in Fig. 5 for bending resistance.

Heavy hard-nip calendering, which does not contribute to the tensile stiffness (Fig. 2), naturally reduces bulk, as seen in Fig. 6, thus reducing the bending stiffness. On the other hand, beating the reinforcement pulp increases tensile stiffness (Fig. 2) but contributes to the bulk of the reinforced sheets only negligibly (Fig. 6). Thus increased beating makes the paper somewhat stiffer in bending.

Just as the increment of softwood pulp to hardwood kraft pulp did not increase the tensile stiffness index of the paper (Fig. 3), it neither contributes to the bulk of the paper, as seen in Fig. 7. Thus the bending stiffness remains unaffected.

TENSILE STRENGTH AND RUPTURE STRAIN

One can argue that the tensile strength of paper arises from fiber strength, bond strength, relative bonded area, and fiber dimensions (34–38). However, the complexity of the phenomena occurring during plastic straining means that courageous assumptions must be made to resolve *how* such quantities affect



6. Bulk of groundwood paper as a function of the mass proportion of four chemical reinforcement pulps at two levels of calendering for lightly beaten pulp (left) and heavily beaten pulp (right) (95% confidence limits are shown)

paper strength (4, 5, 39). The resultant models are difficult to verify, and many of them have a low predictive or explanatory value (40, 41).

The tensile strength can simply be interpreted as the product of Young's modulus and the greatest elastic strain the material can tolerate. The tensile stiffness of restraint-dried paper does not change drastically during straining (42–45), and the Young's modulus and tensile strength of paper often are strongly correlated (41, 46), implying that the variation in elastic modulus is the main source of tensile strength variation, the scattering of the elastic component of rupture strain being smaller, although not insignificant (45).

If we accept the shear-lag mechanism of bond failure (1–3), interfiber bonds close to the fiber ends should be most stressed, and thus they should fail first. This might allow greater total rupture strain in paper consisting of long fibers. However, even if this did happen, we would not know much about the elastic component of the total paper strain.

Fortunately, the elastic component of paper strain can be approached by means of a simple deformation plasticity continuum theory (5, 47). Since deformation occurs in a way that minimizes potential energy, the elastic component ϵ_e of the total strain ϵ in the range of plastic

straining is

$$\epsilon_e = \frac{A\epsilon + \epsilon_y}{1 + A} \quad (2)$$

where

ϵ_y = yield strain

and A is a parameter that can be determined from the shape of the stress-strain curve, referring to the ratio of the elastic-plastic tangent modulus to the distinction between the initial modulus and the tangent modulus.

All these parameters have positive values in tensile loading, and the yield strain of paper appears to be constant, at least for a given drying restraint (48). Thus we find that the elastic strain increases with the total strain. As long as the other quantities in Eq. 2 remain constant, the greater the total rupture strain, the greater are the elastic strain (45) and the tensile strength.

However, there is no theoretical or phenomenological model that can satisfactorily predict or explain the total rupture strain or its elastic component. Equation 2 only describes how the total strain is distributed into elastic and plastic components. This makes it very difficult to understand the effect of fiber properties on the tensile strength of paper.

We can thus expect the increment of softwood kraft pulp to increase tensile strength when it in-

creases Young's modulus, or when it increases rupture strain without reducing Young's modulus. In the case of reinforced groundwood papers, both tensile stiffness index (Figs. 1 and 2) and rupture strain (Fig. 8) are increased, so that a clear increment in tensile strength index can be expected.

This is confirmed by the results in Fig. 9, which shows that increasing the softwood kraft pulp proportion from zero to 50% increased the tensile strength index by an average 68%, while the tensile stiffness index increased by 56% (Fig. 1). The relative change in the elastic component of rupture strain is

$$\frac{\epsilon_{e2} - \epsilon_{e1}}{\epsilon_{e1}} = \frac{(T_2/E_2) - (T_1/E_1)}{(T_1/E_1)} \quad (3)$$

where

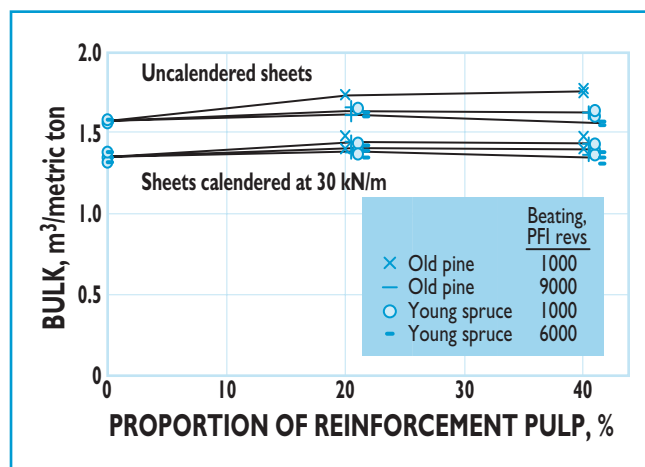
ϵ_e = elastic rupture strain

T = tensile strength

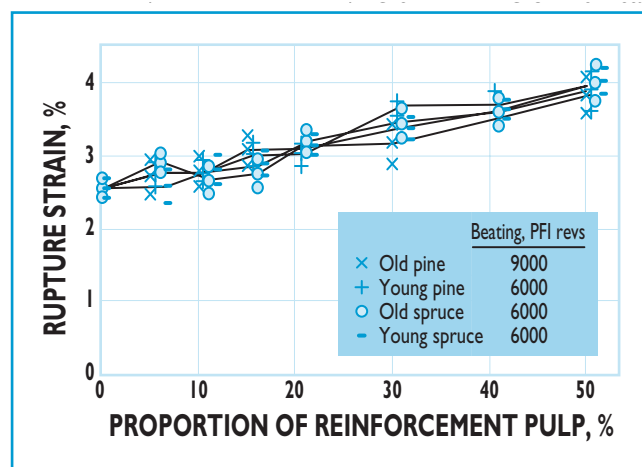
E = tensile stiffness

and the subscripts 1 and 2 represent the state of a variable without reinforcement and after reinforcement, respectively.

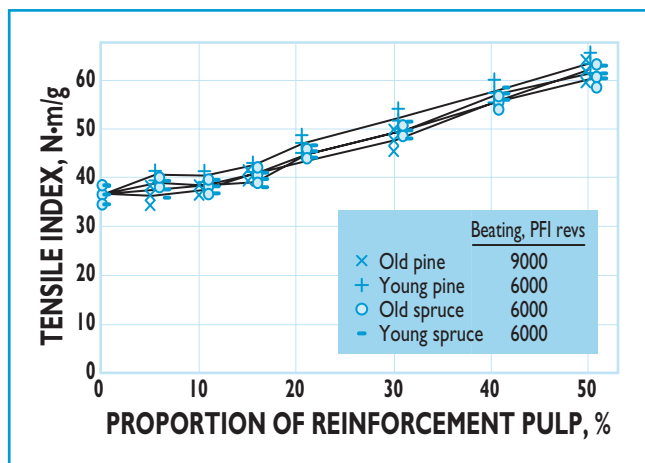
Equation 3 proposes that in this particular case, the elastic rupture strain increased by 8% as the softwood kraft pulp proportion increased from zero to 50%. This is in reasonable agreement with Eq. 2, since the total tensile rupture strain increased by 41% (Fig. 8).



7. Bulk of wood-free paper as a function of the mass proportion of two chemical reinforcement pulps at different levels of beating for uncalendered and lightly calendered sheets (95% confidence limits are shown)



8. Tensile rupture strain of groundwood paper as a function of the mass proportion of four chemical reinforcement pulps (pulps beaten to 40–50°SR; sheets calendered at 30 kN/m; 95% confidence limits are shown)



9. Tensile strength index of groundwood paper as a function of the mass proportion of four chemical reinforcement pulps (pulps beaten to 40–50°SR; sheets calendered at 30 kN/m; 95% confidence limits are shown)

The tensile strength index of reinforced groundwood paper shows a clearly pronounced nonlinearity as a function of the proportion of reinforcement pulp, as seen in Fig. 9. Others have made similar observations (49–52). Rather than percolation nonlinearity (11, 12, 16), this is probably due to the mechanical pulp dominating the rupture strain of paper at low concentrations of kraft pulp, as suggested previously (52).

As in the case of tensile stiffness, extended beating of the reinforcement pulp increases the tensile strength index of reinforced groundwood papers, as seen in Fig. 10. On the other hand, the tensile strength index clearly decreases with calendering (Fig. 10), although the tensile stiffness remains unaffected (Fig. 2). This phenomenon is obviously due to the hard-nip calendering deteriorating

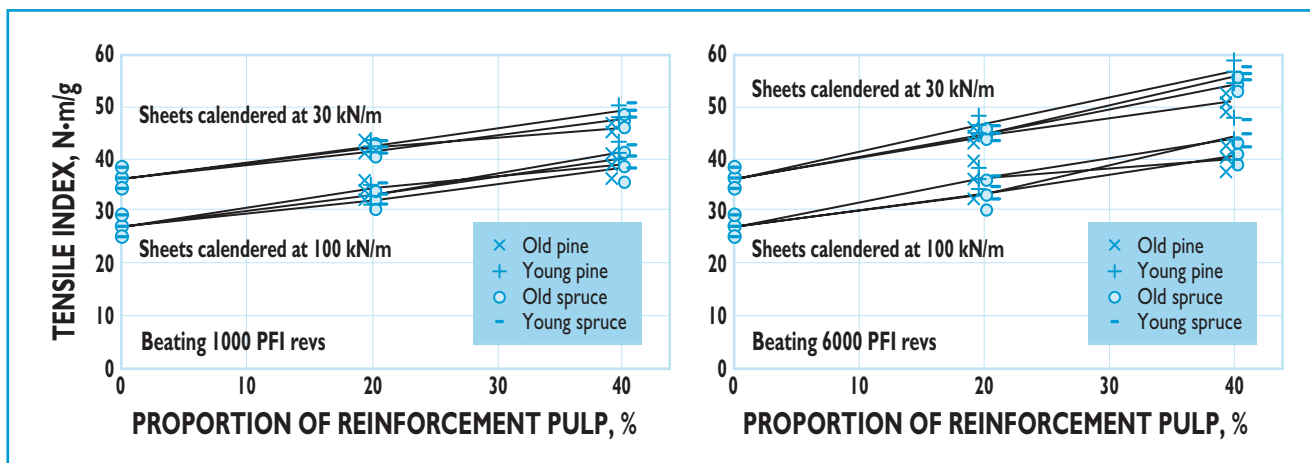
fibers or fiber bonds so that heavily calendered paper does not tolerate as great a strain as lightly calendered paper. The rupture strain is strongly affected by calendering, as seen in Fig. 11. This phenomenon may depend on calendering conditions. Results on the relative decrements in sheet mechanical properties with calendering vary (31–33).

The increment of softwood pulp proportion in the wood-free paper increases neither tensile stiffness index (Fig. 3) nor rupture strain. The tensile strength index is affected only slightly if at all, depending on softwood pulp beating, as seen in Fig. 12. Naturally, this phenomenon might change if low-cohesion fillers were added.

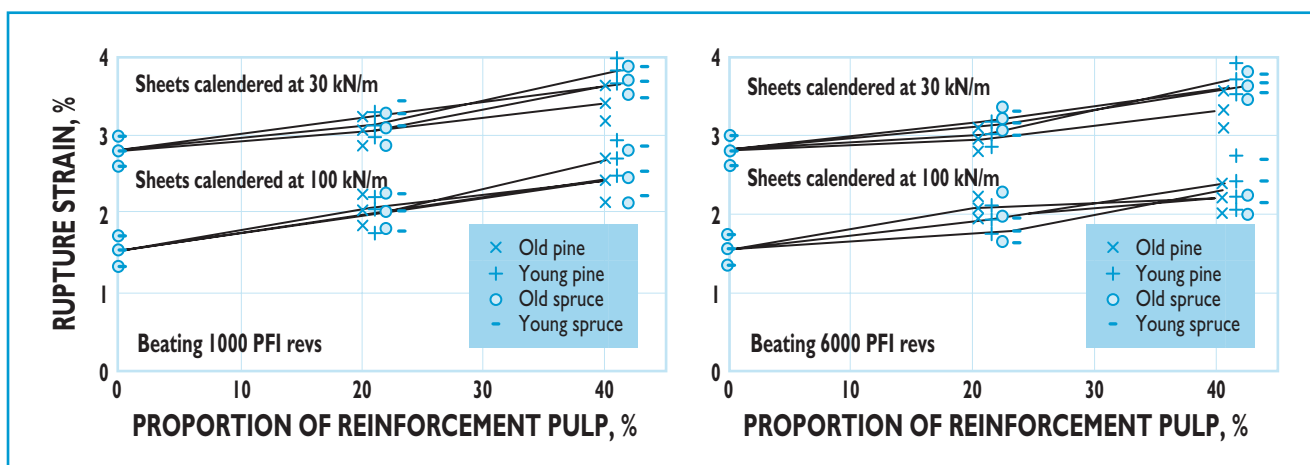
It was hypothesized earlier that where interfiber bonds first fail close to fiber ends, papers made from long fibers might be more extensible. However, no signs of such behavior are seen in Fig. 8, nor does the rupture strain increase when softwood kraft pulp is blended with hardwood kraft pulp (cf. Figs. 3 and 12). Thus it is questionable whether the shear-lag analysis (1–3) can be extended for plastic deformations. This also means that simple phenomenological theories on the effect of fiber properties on tensile strength do not yield realistic approximations.

FRACTURE ENERGY

Defects greatly reduce the strength of an object. A crack can propagate even when the average strain within the material is well below the point of fracture for a homogeneous specimen. According to the fundamental papers by Griffith (53) and Irwin (54), the condition for this is that the potential energy stored in the object decreases during crack propagation, i.e., the elastic energy stored in the specimen is released at least at the same rate as the creation of new surfaces consumes energy.



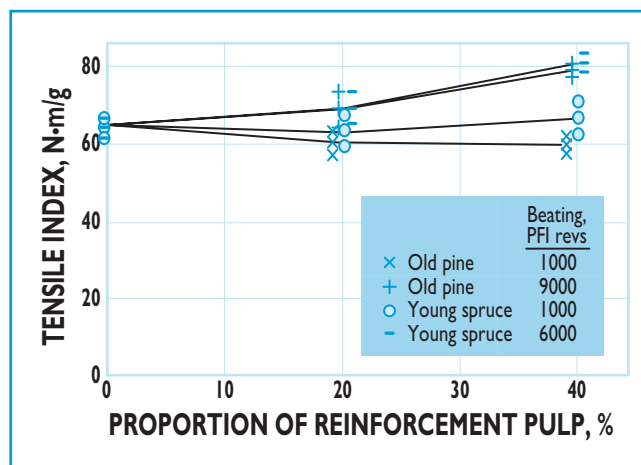
10. Tensile strength index of groundwood paper as a function of the mass proportion of four chemical reinforcement pulps at two levels of calendering for lightly beaten pulp (left) and heavily beaten pulp (right) (95% confidence limits are shown)



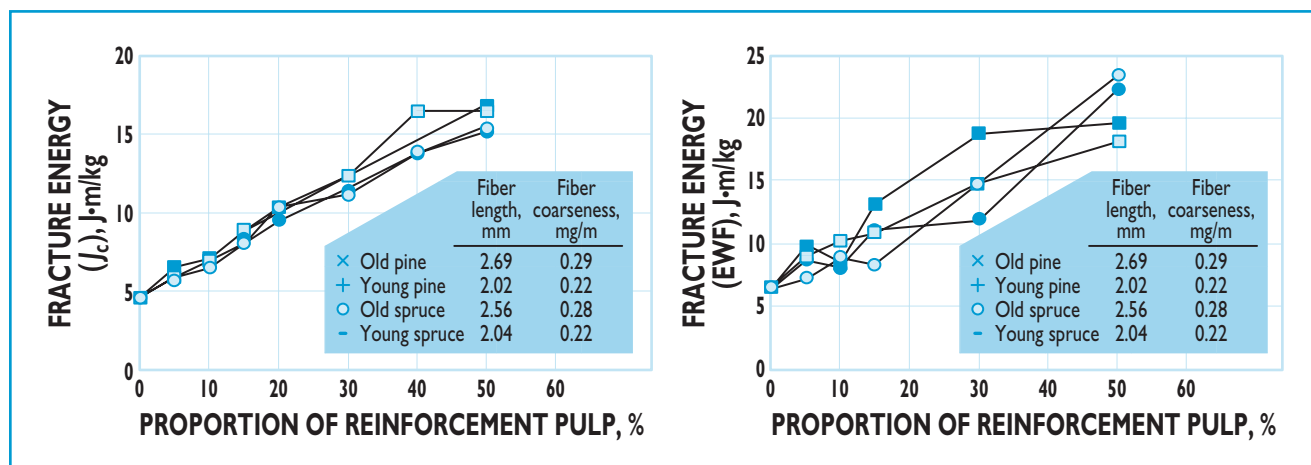
11. Tensile rupture strain of groundwood paper as a function of the mass proportion of four chemical reinforcement pulps at two levels of calendering for lightly beaten pulp (left) and heavily beaten pulp (right) (95% confidence limits are shown)

The work needed to overcome molecular cohesion is a fundamental material property unaffected by the dimensions of the body or by the external forces introduced. In real materials, plastic deformations occur in the vicinity of the crack tip. This local plastic work has to be done in order to propagate the crack, and it has to be included in the concept of fracture energy (55, 56). The fracture energy (or toughness) may determine the “strength” of an object with a flaw of specified dimensions, i.e., the critical nominal stress. Generally, when the toughness is known, the critical values of the nominal stress within an object can be calculated for different flaw dimensions (57, 58).

We can easily imagine that when softwood kraft pulp is added to a paper furnish, the work needed to separate molecules from each other in order to propagate a crack, as well as the work consumed in associated plastic deformations, are affected. The toughness certainly depends on the chemical character of the bonds between



12. Tensile strength index of wood-free paper as a function of the mass proportion of two chemical reinforcement pulps at different levels of beating (sheets calendered at 30 kN/m; 95% confidence limits are shown)



13. Fracture energy index of groundwood paper as a function of the mass proportion of four chemical reinforcement pulps (pulp beaten to 40–50°SR; sheets calendered at 30 kN/m); Left: STFI J_c ; Right: EWF

microscopic particles. However, it is reasonable to assume that both bond properties and fiber morphology affect the fracture energy. Such effects can be conveniently understood within the framework offered by Barenblatt (59) and Dugdale (60) for elastic-plastic materials.

For an ideally elastic-plastic material, the work consumed by crack propagation equals the product of the yield stress of the material and the width of the fracture process zone, multiplied by specimen thickness and the length of crack increment (59, 60). In the case of nonideally elastic-plastic (or strain-hardening) material, the “yield stress” may be conveniently replaced by some kind of combination of the actual yield stress and the tensile strength of the material, such a combination obviously characterizing the stress conditions within the plastic zone (61, 62). This implies a relation between the toughness and the tensile properties of paper: The stronger the paper, the tougher it is. On the other hand, the more ductile the paper is in plastic straining, the wider is the fracture process zone. Further, the lower the yield stress, the wider is the fracture process zone where plastic deformations take place.

This discussion does not tell us much about the effect of fiber dimensions. However, as long as fibers do not break extensively, the width

of the fracture process zone must depend linearly on fiber length (63), since cohesion exists between the crack faces as long as some of the fibers are bonded on both sides. In other words, fiber length determines the greatest crack tip opening displacement where cohesion still exists. Most experimental observations indicate that the fracture energy of paper depends linearly on fiber length (63–65).

Taking a microscopic point of view, the work needed to release a fiber by bond failure arises from the work needed to break one bond multiplied by the number of bonds that have to be broken. Thus the fracture energy depends linearly not only on fiber length, but on the relative bonded area and the work needed to break a bond. However, these linear dependencies are strictly valid only as long as fibers do not fail (63). The other extreme is that in the case of very weak fibers and strong bonds, the fracture energy of paper arises from the work needed to break fibers (63).

Practical cases that fall between these extremes can be described using an equation from a previous work (66):

$$W_{\text{fiber}} = N_f w_f + L_{\text{debond}} w_l \quad (4)$$

where

W_{fiber} = fracture resistance per fiber

N_f = fraction of breaking fibers

L_{debond} = debonded fiber length

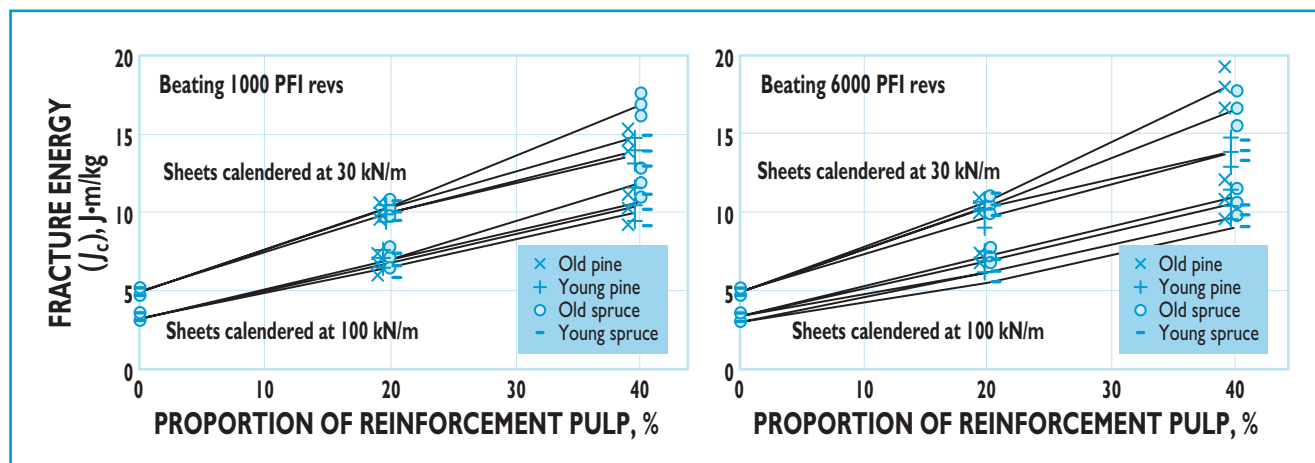
w_f = fiber rupture energy

w_l = bond-breaking energy per unit length.

Both N_f and L_{debond} are measurable quantities related to each other through fiber length distribution and fiber failure probability. In contrast, w_f and w_l are phenomenological parameters whose dependence on measurable fiber and bond properties must be traced more or less indirectly (63, 66).

Based on this discussion, we can expect that the fracture energy of paper depends heavily on fiber length. Consequently, the increment of softwood kraft reinforcement pulp should considerably increase the fracture energy of both mechanical and wood-free papers. Figure 13 illustrates this in the case of reinforced groundwood papers.

In Fig. 13, the fracture energy index of reinforced groundwood paper is measured by two independent methods: the J -integral method based on one notch length (developed by the Swedish Pulp and Paper Research Institute) (67,68) and the essential work of fracture (EWF) method (61,62,69). The effect of the reinforcement pulp on the fracture energy of paper is very considerable. According to both measures, the fracture energy index increases by



14. Fracture energy index of groundwood paper as a function of the mass proportion of four chemical reinforcement pulps at two levels of calendering for lightly beaten pulp (left) and heavily beaten pulp (right) (95% confidence limits are shown)

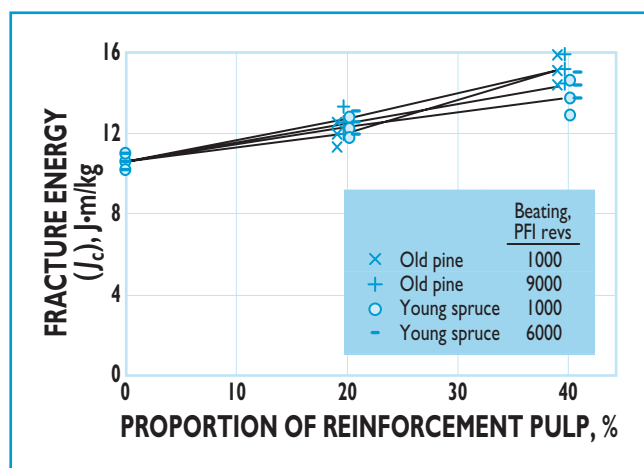
200–250% as the proportion of reinforcement pulp increases from zero to 50%.

Figure 13 (left side) also shows that different softwood kraft pulps reinforce the furnish quite differently. This discrepancy arises from different fiber lengths, the cell-wall thickness showing no importance provided that the fibers are well beaten (70). The variation in reinforcing efficiency, in turn, means that favorable optical properties can be achieved with a smaller proportion of the most effective kraft pulps (70). However, this difference can be distinguished only by the *J*-integral method because of the large random scattering of the EWF measurement (71).

Figure 14 shows that the fracture energy decreases considerably with calendering. This decrement is at least as pronounced as the decrement in tensile strength (Fig. 10). It is also clear that the fracture energy increases with increased beating of reinforcement pulp, mainly in the case of pulps produced from old-growth trees, these fibers having the greatest fiber length and cell-wall thickness (Fig. 13). However, it has been shown that the particular method used to produce Fig. 14 does not completely agree with reference methods, specifically with respect to beating (71). Indeed, the effect of beating may be stronger than shown in Fig. 14 (71).

Unlike other mechanical properties, the fracture energy of wood-free paper clearly and consistently increases with an increasing proportion of softwood kraft pulp, as seen in Fig. 15. This is understandable, since unlike the other properties, the fracture energy is a linear function of fiber length (63–66). Figure 15 also shows that softwood fibers originating from old-growth trees reinforce the paper somewhat more effectively than shorter fibers from young trees.

A previous work showed that the fracture energy index of paper is a linear function of the proportion of reinforcement pulp within a furnish (71), and this is also



15. Fracture energy index of wood-free paper as a function of the mass proportion of two chemical reinforcement pulps at different levels of beating (sheets calendered at 30 kN/m; 95% confidence limits are shown)

reflected in Fig. 13. This means that the reinforcing effect of softwood kraft pulp may be evaluated from pure kraft pulp sheets, which considerably simplifies pulp testing.

A COMMENT ON DIMENSIONAL STABILITY

Dimensional changes in paper as a function of moisture content are important in office papers, which lose moisture during laser printing or photocopying processes, and in offset papers, where the paper is moistened several times during printing. The drying shrinkage may be irreversible at first, but it has been shown to become reversible with further cycles (72, 73).

Hygroexpansivity is not very sensitive to the type of pulp used, not even between mechanical and chemical pulps (73–75). Indeed, the hygroexpansivity of restraint-dried softwood kraft pulp sheets is not sensitive to wet pressing, bonding agents, beating, or fiber length

(74–78). On the other hand, the in-plane hygroexpansivity of freely dried paper correlates positively with Young's modulus (75–77). It has been suggested that this is due to axial fiber deformations dominating hygroexpansivity in restraint-dried sheets, whereas transverse fiber deformations make a considerable contribution in freely dried sheets, where the fiber structures are not completely oriented along the paper plane (75, 79).

CONCLUSIONS AND DISCUSSION

The tensile stiffness and tensile strength of reinforced groundwood paper increase with increasing proportion of softwood kraft pulp. However, with modern, efficiently bonding pressure groundwood, the increment in these properties is moderate. In the case of tensile strength, the increment is also clearly nonlinear. Thus small amounts of chemical pulp do not reinforce the paper. The bending stiffness of reinforced groundwood paper was not affected by reinforcement pulp, since the increment of tensile stiffness is offset by somewhat reduced bulk.

On the other hand, the effect of reinforcement pulp on the fracture energy of the reinforced groundwood paper is very considerable. Assuming that the fracture energy—together with flaw size distribution—determines the greatest load a paper web can carry, the increment in fracture energy justifies

including softwood kraft pulp in mechanical printing papers. Thus it may be feasible to evaluate softwood reinforcement pulps on the basis of their contribution to the fracture energy. Certainly the effect of fiber properties and papermaking treatments on the fracture energy deserve further research.

The tensile stiffness, bending stiffness, and tensile strength of wood-free kraft paper are only moderately affected by increasing the proportion of softwood kraft pulp, a finding that agrees with most previous observations (80–84). However, the fracture energy is considerably increased, since it is a strong function of fiber length. This situation might change for sheets containing a large proportion of debonding agents (e.g., mineral fillers), since in the case of low bonding, fiber length also contributes to stiffness and strength.

EXPERIMENTAL

Four bleached softwood laboratory kraft pulps of different wood origin were blended with commercial pressurized groundwood of 44 mL CSF and commercial birch kraft pulp, mean fiber length 0.9 mm. White-water recirculation was used in both cases. There were no major differences in the zero-span tensile indices of well-bonded softwood kraft handsheets. The length-weighted mean values of the fiber length and coarseness of the pulps varied between

2.0–2.7 mm and 0.22–0.29 mg/m, respectively. These measures are shown in detail in Fig. 13.

Throughout the beating experiments, the PFI mill was loaded with 35 g of pulp instead of 30 g. Cylinder-dried handsheets of 50 g/m² were prepared and calendered in a hard-nip laboratory calender (18-cm diam.) at 23°C and 50% relative humidity with a feeding speed of 10 m/min. Two calender nip passes were used for each treatment. Standard testing conditions were used in tensile testing of the papers, with the exception of straining velocity, which was 99%/min. Complete tables of experimental findings are available in the literature (85). **TJ**

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