Influence of knot fibers on TMP properties

Ulla Sahlberg

*ABSTRACT: The influence of knot fibers on the properties of thermomechanical pulp was studied by blending knots with knot-free wood chips from Scandinavian spruce (*Picea abies*). Knots consist mostly of compression-wood fibers, which are morphologically different from normal wood fibers. Knots also have a low moisture content, with a basic density twice that of normal wood. The investigation shows that handsheets containing knot fibers have inferior strength, light absorption, and surface properties. These effects are related to the chemical composition and the morphological properties of the knots.*

KEYWORDS: Cations, compression wood, extractives, knots, mechanical properties, optical properties, Picea abies, *thermomechanical pulping.*

Trees contain several types of fiber: normal earlywood and latewood, compression wood, and juvenile and mature wood. These various fiber types are formed to transport water and minerals while supporting the living tree stem.

The chemical composition and morphology of the walls of these fibers can vary considerably, probably because of their different functions. These differences affect the mechanical properties of the fibers and thus influence their papermaking properties. Moreover, the distributions of the various types of fibers can differ for trees grown in different locations, even within the same wood species. Variations in the type and distribution of fibers in wood raw material can lead to variations in pulp quality, especially in mills producing thermomechanical pulp (TMP), where the possibility of modifying fiber properties is less than in chemical pulping.

An important source of variation in the wood raw material is the presence of compression-wood fibers in knots and stemwood. Compression-wood fibers have a higher lignin content than normal wood fibers *(1)*, and there are major differences in their cell-wall structure. Compression-wood fibers lack the S_3 layer and have a thick S_1 layer. The S_2 layer contains helical cavities towards the lumen, and these cavities follow the microfibril angle. The microfibril angle in the S_2 layer is especially important for the stiffness of the fibers in the direction of the fiber axis, with smaller angles resulting in stiffer fibers *(2)*. This angle is always larger in compression-wood fibers than in normal wood fibers.

Knots are composed mostly of compression wood, with the balance consisting of opposite and normal wood *(1)*. The compression wood in knots can easily be removed from the process by screening overthick chips, which are often caused by knots. In contrast, compression wood from the stem cannot be screened, so it enters the system along with the accept chips.

Knots also contain large amounts of extractives and have a lower moisture content than normal wood. Indeed, the basic density of knots is twice that of normal wood *(1)*. Clearly, the mechanical properties of knot fibers are different from those of normal fibers. It can therefore be expected that knots will influence refining and affect the quality of TMP.

The aim of this work was to investigate how knots in the wood raw material influence the quality of TMP and to relate these results to the morphological and chemical properties of the knot fibers. Scandinavian spruce (*Picea abies*), which is normally used for TMP production in Sweden, was used in these studies. Various amounts of pure

Sahlberg is a research engineer at STFI (Swedish Pulp and Paper Research Institute), Box 5604, S-114 86 Stockholm, Sweden.

I. Lignin content and carbohydrate composition of spruce chips and knots, % of weight

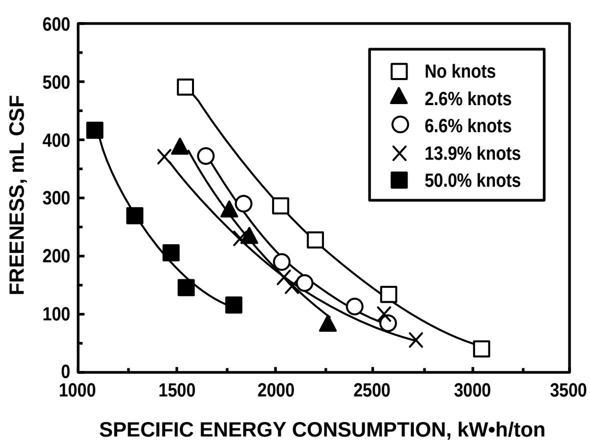
	Chips	*Knots*
Lignin (Klason)	27.6	34.9
Cellulose	43.6	27.9
Glucomannan	12.0	7.7
Galactan	2.3	10.2
Arabinan	1.2	1.5
Xylan	5.5	5.8
Extractives *	1.0	11.0

* Soluble in dichloromethane

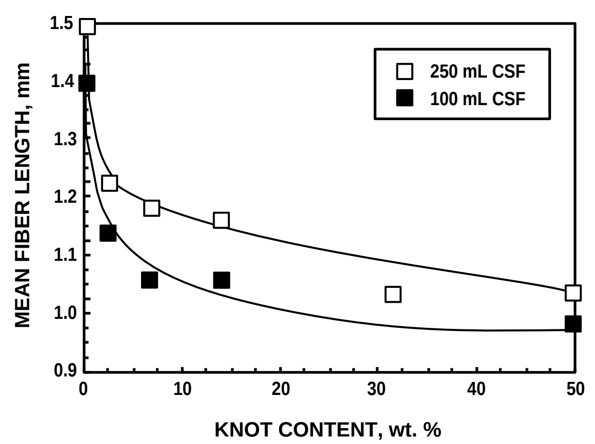
II. Inorganic ions in spruce chips and knots, mg/kg

	Ca^{2+}	*Na^{+}*	*Fe^{2+}*	*Mn^{2+}*
Knots	3070	1	13	390
Chips	690	32	32	110

1. Pulp freeness as a function of specific energy consumption for pulps at five levels of knot content



2. Mean fiber length as a function of knot content for pulps at two levels of freeness



knots without any surrounding stemwood were blended with normal knot-free stemwood chips to produce TMP in a laboratory refiner. The blend with the smallest amount of knots (2.6% by weight) can be considered to represent a normal input to a typical TMP mill.

Experimental

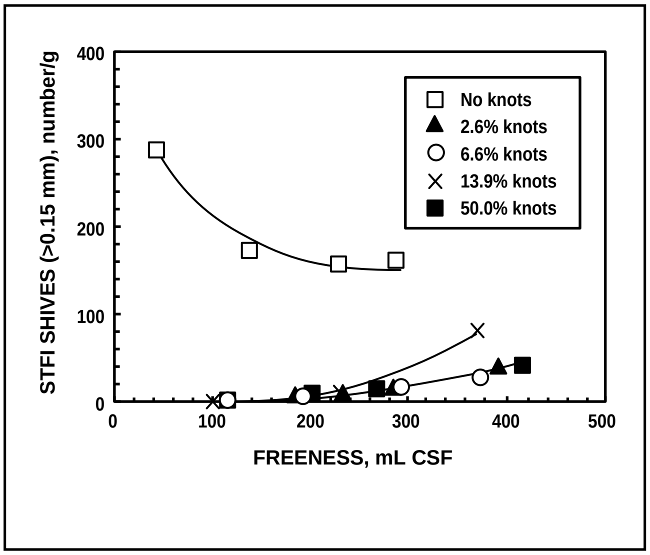
Raw material

Pure knots (without any normal wood) were picked by hand from a chip washer at a Swedish TMP mill using spruce. Chips of pure knots are rare. Knots are usually found combined with surrounding stemwood in overthick chips. It has been estimated that 60% of overthick chips contain knots and that 90% of the knots are found in the oversize chip fractions *(3)*. However, pure knots can be found in the reject flow from chip washers at a TMP mill, where a proportion of the knots are separated from the normal chips because of their relatively high specific weight.

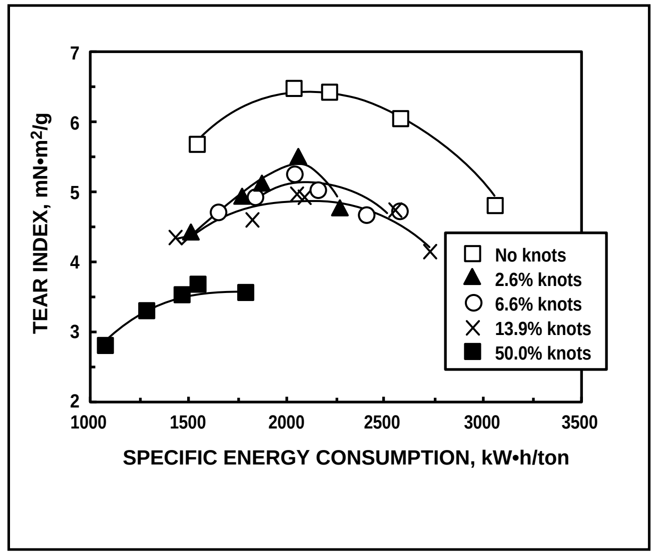
Before refining in the laboratory, the knots were blended with screened knot-free chips (2–6-mm thickness) of normal Scandinavian spruce roundwood in five different ratios. The normal screened chips were sorted by hand, and all chips dark in color and containing knots were rejected. The weight percentage of knots in the blends were: 0, 2.6%, 6.6%, 13.9%, and 50.0%.

To study the influence of extractives in the knots, trials were also made with knots that had been extracted for 48 hours with warm ac-

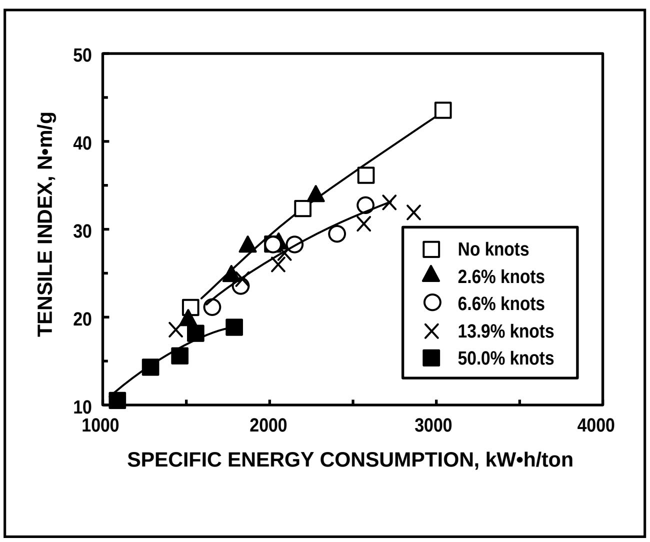
3. STFI shives as a function of freeness for pulps at five levels of knot content



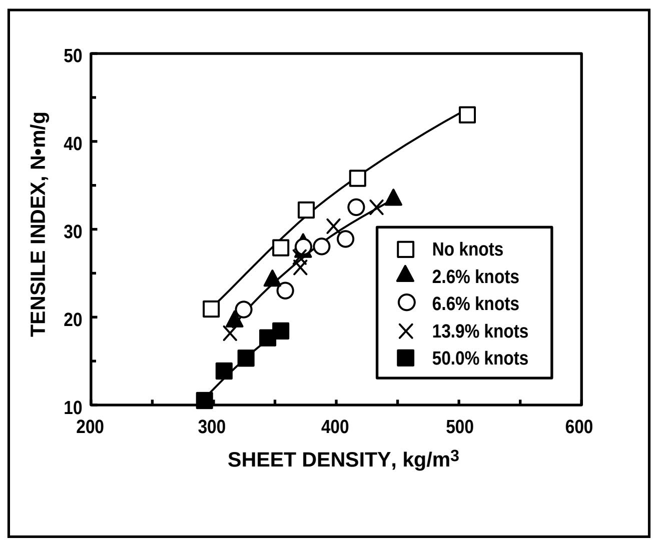
4. Tear index as a function of specific energy consumption for pulps at five levels of knot content



5. Tensile index as a function of specific energy consumption for pulps at five levels of knot content



6. Tensile index as a function of sheet density for pulps at five levels of knot content



etone. These extracted knots were blended with unextracted chips and refined in two stages. The amount of knotwood used in these trials was 50% by weight, an amount chosen to accentuate the response in the refining.

To study the influence of cations, which knots contain in abundance, Ca^{2+} was removed by treating a pulp containing 50% extracted knot fibers with a chelating agent [diethylenetriamine pentaacetic acid (DTPA)] at neutral pH prior to the second-stage refining. DTPA was charged in excess (200% of the amount needed to chelate the amount of calcium present).

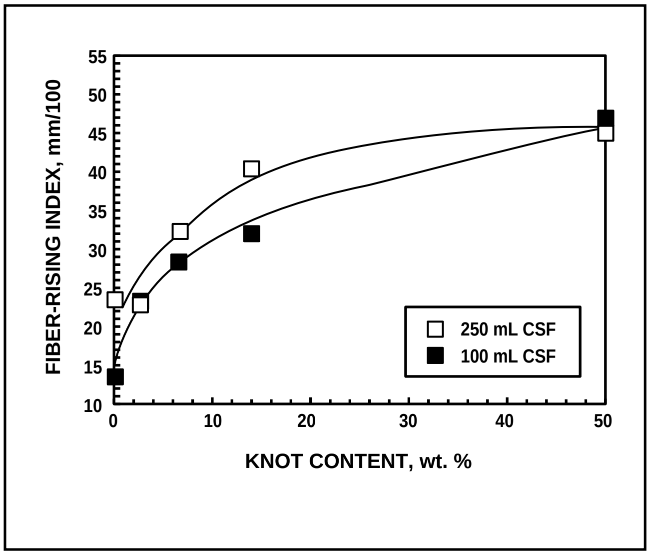
Refining

The moisture contents of the knots and chips were equalized by preheating each blend for 10 min at 135°C and then soaking them in water under pressure for 5 min prior to refining. Each blend was refined in two stages to a freeness of about 100 mL CSF in a pressurized pilot-plant refiner with 12-in. plates (150 kW) and a discontinuous preheater.

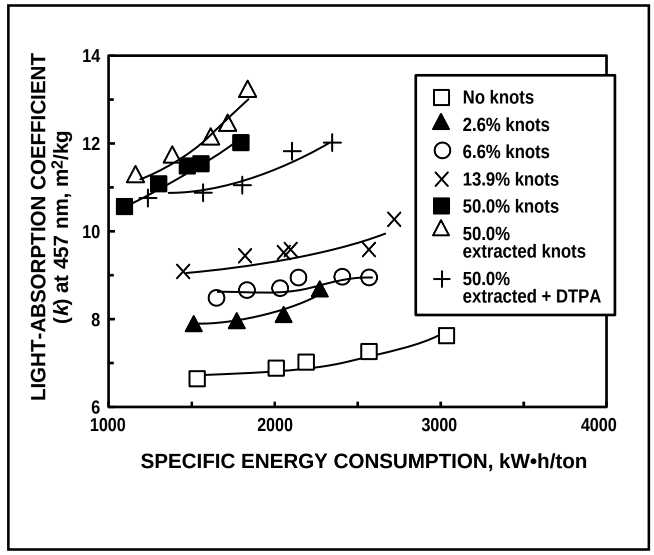
Bleaching

The refined pulps were treated with DTPA at neutral pH, heated, and bleached with hydrogen peroxide in plastic bags in thermostated water baths. Bleaching liquor was mixed into the pulps by kneading the bags. Charges of bleaching chemicals were:

7. Fiber-rising index as a function of knot content for pulps at two levels of freeness. (The fiber-rising index is expressed in terms of fiber length, measured in millimeters, per 100 measurements of fibers longer than 0.1 mm.)



8. Light-absorption coefficient *k* (457 nm) as a function of specific energy consumption for pulps at various levels of knot content



4% H_2O_2, 4% sodium silicate (technical quality), and 0.1% $MgSO_4$ by weight of pulp. The initial pH of the bleaching liquor (measured at room temperature) was adjusted to 11.5 by addition of NaOH.

Analyses

All analyses and testing of raw materials and pulps were done according to SCAN test standards or by specific methods identified in the discussion.

Results

Wood material properties

Table I shows the chemical compositions of the raw materials as determined by the method of Theander and Westerlund *(4)*. The knots used in this study contained 20% more lignin and 38% less cellulose than normal wood chips. The galactan content was high in the knots, which is typical for wood containing compression-wood fibers *(1)*.

Table II shows the metal contents of the materials determined by a method based on atomic absorbency. Metal ions are of interest, since some cations such as Mn^{2+} catalyze peroxide decomposition during bleaching of mechanical pulps. The Ca^{2+} and Mn^{2+} contents of knots were much higher than in normal spruce wood.

Both compression and normal wood fibers in knots are short and have thick walls. Therefore, the pure knots used here had a high basic density of 880 kg/m^3, compared with 385 kg/m^3 for the normal wood used in this study. The compact structure and high extractives content of knots may impede water from penetrating the knotwood structure. The measured dry matter content was 75% for the knots compared with 45% for the normal wood.

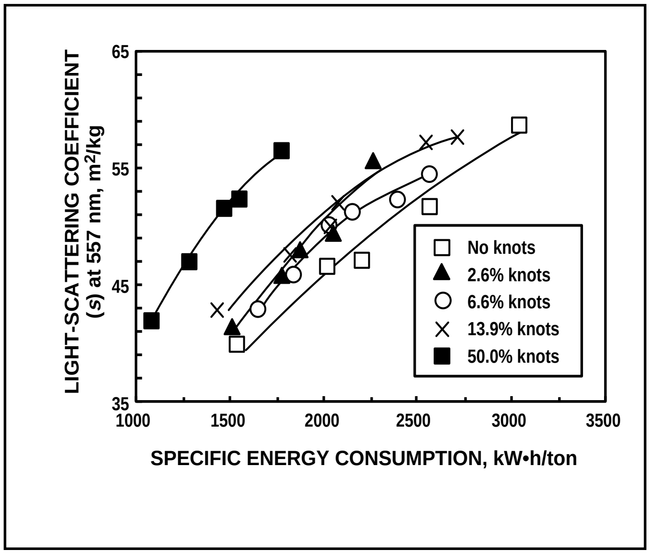
Refining trials

Figure 1 shows that the presence of knots in the raw material has a large influence on the specific energy required to reach a given level of freeness. Even with only 2.6% knots added to the chips, the power consumption was reduced. Further addition of knots produced no significant effect on the specific energy consumption until an extremely high amount of knots (50%) was added to the wood raw material.

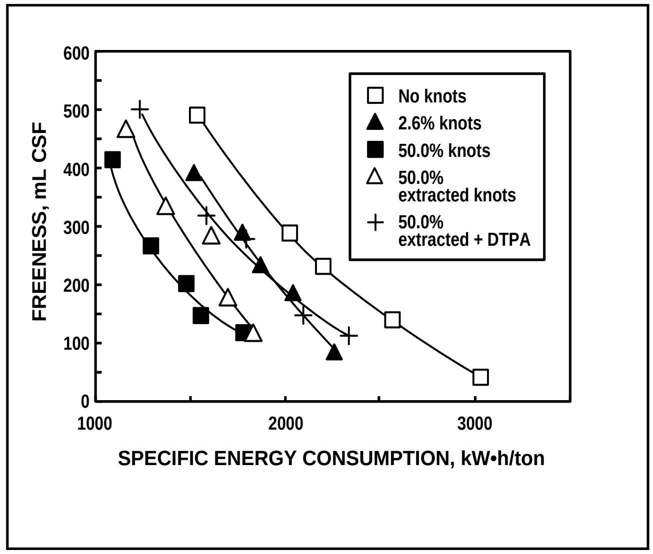
Figure 2 shows the mean fiber length of the pulps (measured with the Kajaani FS 200) at various levels of knot addition. The presence of even a small amount of knots in the raw material decreased the mean fiber length of the pulps. One explanation for the decreasing fiber length may be that knot fibers are shorter (measured to 1 mm) than normal wood fibers. However, the reduction in fiber length was not linear with knot percentage, and the reduction was greater than expected. This suggests that the normal fibers experience a high frequency of fiber cutting when knots are present. The amount of shives also decreases when knots are present, as shown in **Fig. 3**. The high frequency of fiber cutting and the shive reduction indicate that the presence of knots changes the mechanics of the refining process, thereby affecting the refining of the normal wood fibers.

Tear index is directly dependent on the pulp's long-fiber content. Given the short mean fiber length of the TMPs containing knot fibers, it was not surprising to find that tear index decreased with increasing knot content, as seen in **Fig. 4**. The decrease is significant even at 2.6% knot content. However, tear index did not decrease further with in-

9. Light-scattering coefficient *s* (557 nm) as a function of specific energy consumption for pulps at five levels of knot content



10. Pulp freeness as a function of specific energy consumption for pulps at various levels of knot content



creasing knot content until 50% knots were added to the chips. Normally, variations in the freeness of the first-stage pulps influence the tear index after the second stage *(5)*. However, variation in the freeness level of the first-stage pulps was negligible in this investigation (655–695 mL CSF).

At a given energy consumption, the presence of knots had no significant influence on the tensile index at the lowest knot content, as seen in **Fig. 5**. Higher amounts of 6.6% and 13.9% decreased the tensile index somewhat, while an addition of 50% knots led to a considerable decrease in tensile strength. **Figure 6** shows tensile index as a function of sheet density. Comparison at a given sheet density reveals that the decrease in tensile index was significant even at a knot content of only 2.6%. Apparently, this is due to the higher sheet density obtained at the same specific energy level by the addition of knot fibers.

Surface properties of the handsheets were determined in terms of both Bendtsen surface roughness and the fiber-rising index. The latter is an important property related to printing and is measured with STFI's Fibro 1000 analyzer. The surfaces of handsheets made of knot pulps were smoother than those of sheets made of the reference pulp with no knots. This was not totally unexpected, since the pulps with knot fibers contained more fines, which could fill in voids between fibers on the sheet surface, making it smoother. **Figure 7** shows the fiber-rising indexes of the pulps at various levels of knot content. The sheet with the lowest knot content had a significantly higher fiber-rising index than the reference sheet with no knots, and the index continued to increase with increasing knot content. This is probably because of the poor bonding properties of the knot fines—a function of their structure and high stiffness—which allow the fibers to rise easily from the sheet surface.

The light-absorption coefficient at 457 nm, *k*, was higher in pulps containing knot fibers, as seen in **Fig. 8**. This can be explained by the higher lignin and extractives content of the knots. The *k* values increased with the amount of knots added to the chips. At a knot content of 50%, *k* was very high, possibly near the limit where it can be measured with the method used. **Figure 9** shows that the light-scattering coefficient at 557 nm, *s*, also increased with knot content, the result of higher fines contents.

Effect of extractives and cations

Knots are rich in extractives, which are hydrophobic and thus hinder water penetration. Removal of the extractives from the knots (at a knot addition of 50%) resulted in a slightly higher specific energy consumption at a given freeness value, as seen in **Fig. 10**.

Cations can inhibit fiber swelling, so DTPA was used to remove cations from extracted knots. As seen in Fig. 10, DTPA treatment further increased energy consumption at a given level of pulp freeness.

Extraction of the knots alone did not affect the mean fiber length of the pulps, but extraction with DTPA treatment slightly increased the mean fiber length. This increase in fiber length apparently had a positive effect on tear index, which was slightly higher (at a given level of specific energy) for the DTPA-treated pulps than for the two other pulps at 50% knot content (extracted and nonextracted).

The difference in tensile index was not significant at the same level of specific energy, but comparison at a

III. Brightness, light-absorption coefficient, and hydrogen peroxide consumption of bleached pulps at three levels of knot content

Knot content, %	Brightness, % ISO	Light absorption coeff. (k, 457 nm) m^2/kg	H_2O_2 consumption, %
0.0	75	1.9	1.6
2.6	72	2.3	1.8
50.0	70	3.3	2.2

given sheet density showed that DTPA treatment of extracted pulp (at 50% knot content) gave a pulp with the same tensile strength as the blend containing 2.6% of unextracted knots.

The light-absorption coefficient, *k*, increased when the knots were extracted, as seen in Fig. 8. However, *k* decreased after DTPA treatment of the pulp containing 50% extracted knots. Still, the light-absorption level for the extracted pulp after DTPA treatment was much higher than for the reference pulp.

The light-scattering coefficient, *s*, decreased for the pulp containing extracted knots and extracted–DTPA-treated knots. DTPA treatment did not improve pulp brightness.

Hydrogen peroxide bleaching

The presence of knots in the wood raw material also influenced the peroxide bleaching of the pulps. This was not unexpected, considering the high lignin and extractives content in the knots. **Table III** shows that a higher knot content leads to lower brightness at the same bleaching conditions. The negative effect on the light-absorption coefficient, *k*, was even larger, but this did not influence the brightness values, since there was a simultaneous increase in light scattering. The peroxide consumption to a given brightness level was also higher for pulps containing knot fibers.

Discussion

The presence of knots in the chips decreases the specific energy consumption of the pulps to a given freeness value compared with a knot-free pulp. At the same energy consumption, pulps containing knots have a lower long-fiber content than knot-free pulps. As a result, strength properties that are directly dependent on the long-fiber content of the pulp, such as the tear index, are also lower for handsheets containing knot fibers. The presence of knots in the raw material also reduced the shive content of the TMP.

The nonlinear decrease in the strength properties and the low shive content of the pulps indicate that knots in the chips influence the refining of the normal fibers. The low mean fiber length of the knot-containing pulps suggests that knot stiffness causes the normal fibers to be crushed and cut in the refiner.

Water is a plasticizer for the wood polymers, lignin, hemicellulose, and the amorphous part of the cellulose, resulting in a decrease in their glass-transition temperatures, T_g. It has been shown that refining should be carried out near or somewhat above the T_g for lignin *(6)*. Knots have a higher dry matter and a higher extractives content than normal wood chips, which may make it difficult, if not impossible, to impregnate them with water, which means that lignin T_g is not lowered. The insufficient moisture content of the knot fibers may, therefore, make the wood material brittle and cause uncontrolled breakage across the fiber walls during refining. The helical cavities in the S_2 layer of the compression-wood fiber walls also may weaken the fiber wall and in this way contribute to fiber cutting. Uncontrolled fiber breakage probably consumes less energy than a proper refining of the fibers, which may explain the lower energy consumption of pulps containing knot fibers.

Good swelling of pulp fibers is important to the development of sheet mechanical properties. It has been shown that cations such as Ca^{2+} impair the swelling properties of wood fibers *(7)*. The Ca^{2+} content of the knots was significantly higher than that of normal wood, so it is possible that the swelling of the knot fibers was low. Given the high concentration of cations and the peculiar morphology of knot fibers, it is likely that pulps containing knots could not be refined to produce a high-quality TMP, even if it were possible to impregnate the knots with water before refining.

However, sheet properties were improved slightly by chemical treatment of knots to remove extractives and metals (cations). The treatments were applied to pulps containing 50% knots, much higher than would normally be present. Nevertheless, the results showed that chemical treatment can change the refining properties of the knots. This suggests that for conventional pulps with lower knot contents, segregation and chemical treatment of knots might provide sufficient improvement of pulp properties.

Clearly, the mechanisms governing the refining of knotwood are complicated. The negative effect of knotwood on TMP properties is probably a combination of several parameters, including insufficient liquor impregnation, the chemical composition of knots, the morphology of knot fibers, and the interactions between knots and knot-free chips during refining.

Conclusions

Knots decrease the quality of thermomechanical pulp. The strength, light absorption, and surface properties of pulps with knot fibers were inferior to those of a pulp produced from knot-free chips. The presence of even small amounts of knots degraded pulp properties significantly.

The degradation of pulp properties can be related to the chemical composition and the morphology of the knot fibers. The high extractives content and compact structure of knotwood impedes penetration of water and chemicals. Knotwood also contains large amounts of metal ions that increase peroxide consumption during bleaching. Moreover, the high extractives and lignin contents in knots reduce pulp brightness after bleaching.

Pulp quality can be improved by removing knots from the process. The question is whether knot removal is profitable. In some cases, the benefits of improved pulp quality may outweigh the cost of removing the knots. TJ

Literature cited

1. Timell, T. E., *Compression Wood in Gymnosperms*, Springer–Verlag, Berlin, Germany, 1986.
2. Page, D. H. and El-Hosseiny, F., *Fiber Sci. Technol.* 8(1): 21(1975).
3. Axegård, P., *Svensk Papperstid.* 81(16): 511(1978).
4. Theander, O. and Westerlund, E. A., *J. Agric. Food Chem.* 34(2): 330(1986).
5. Ferritsius, O. and Moldenius, S., "The effect of impregnation method on CTMP properties," *1985 International Mechanical Pulping Conference Proceedings*, EuCePa, Stockholm, p. 91.
6. Salmén, L., *J. Matl. Sci.* 19(9): 3090(1984).
7. Scallan, A. M. and Grignon, J., *Svensk Papperstid.* 82(2): 40(1979).

The author thanks Bengt Möller for his skillful laboratory work and enthusiasm, Birger Sjögren, Lennart Salmén, Myat Htun, and Ants Teder for comments and discussions on various aspects of this study, and Anthony Bristow for the linguistic revision.

Received for review Feb. 2, 1994.

Accepted Sept. 30, 1994.