Selection of Raw Material Offers new Energy-Property Combinations for Mechanical Pulp

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ABSTRACT

The relationship between various Norway spruce wood fiber properties and TMP fiber properties was studied in order to find alternative energy–property combinations for mechanical pulping. The results show the large differences in the wood fiber property distributions between the different wood lots. The shape of the distributions and the interaction between the fiber properties and the defibration impacts acting on them are stated to have a significant effect on the deformation of the fibers. By selecting Norway spruce wood raw material by the growth rate and the position in the stem the energy–property combinations of TMP could be widely influenced.

INTRODUCTION

Variability of wood fibers offers a poorly utilized tool to influence energy – property combinations of mechanical pulps. At present, there are only a few examples that this possibility has been exploited. In TMP manufacture fiber length and tear strength are controlled by the amount of sawmill chips used and fast-growth raw material is used for purposes where high brightness is required /1, 2/.

Within a tree stem the formation of early and late wood fibers cause variation to the cross-sectional dimensions of fibers. Fiber length is mainly influenced by the age of the cambial tissue where the fibers are formed, while fiber wall thickness between the stems is mainly influenced by the growth rate of the tree. Growth rate has a significant effect on the proportion of juvenile wood and fiber properties of juvenile wood and mature sapwood. Fiber dimensions of juvenile wood at the base of the stem are similar to those at the top of the stem, but heartwood formation may affect the properties of juvenile wood from the tree base. The structure of the fiber wall has also an independent influence on the behavior of wood fibers.

In a European wide EuroFiber project young wood with a high proportion of juvenile wood gave a pulp with good optical properties, but somewhat lower tear index and higher energy consumption. Sawmill chips from old trees of heavy dimensions, required lower energy input and gave higher tear index, but inferior optical properties /2/.

Corson et al have examined the influence of Radiata pine wood properties on mechanical pulp quality in a series of studies /3, 4/. The results have shown that selection for preferred fiber characteristics within a tree species enables paper quality to be optimized and pulp processing costs minimized. One result of the studies was that basic wood density does not have the dominant effect on refining energy consumption, and the properties of fibers should be directly monitored.

Our experiments with slow and fast-growth spruce (Picea abies) showed that the specific energy consumption of the slow-growth wood was smaller to a given freeness than that of the fast-growth wood. Thick walled raw material was more susceptible to fiber cutting than fast-growth material and moving from TMP to high rotational speed and further to PGW reduced the differences of pulps made of fast or slow-growth raw material /5, 6/.

Pressurized grinding of wood samples from different parts of the slow and fast-growth stems resulted in pulps with very different property combinations. The conclusion of the studies was that in addition to the fiber dimensions, wood density and dry solids content the fiber wall structure influences the defibration result /7/.

The current study was designed to relate the pulp fiber properties to various wood fiber properties in order to find alternative energy – property combinations for mechanical pulping.
SELECTION OF WOOD RAW MATERIAL

The wood selection criteria were to obtain wood samples with clearly different fiber dimensions, fiber wall structure, heartwood formation and dry solids content. This was executed by choosing 96 fast grown and 135 slowly grown trees with similar diameter (app. 23 cm) but different age (30 and 99 years respectively), and taking sapwood and heartwood samples from the bottom log, and top log samples from the last pulpwood log of the trunk.

The dry solids content of the chips became more even after the first plug screw of the refiner station being 51-62%, except the dry heartwood samples 64-68%.

Table I  Wood properties of the Norway spruce stems and wood samples.

<table>
<thead>
<tr>
<th>STEMS</th>
<th>SLOW-GROWTH</th>
<th>FAST-GROWTH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bottom log</td>
<td>Top log</td>
</tr>
<tr>
<td>Annual rings</td>
<td>90</td>
<td>34</td>
</tr>
<tr>
<td>Mean annual ring width, mm</td>
<td>1.3</td>
<td>1.8</td>
</tr>
<tr>
<td>Latewood content, area w., %</td>
<td>32</td>
<td>28</td>
</tr>
<tr>
<td>Heartwood, area w., %</td>
<td>50</td>
<td>29</td>
</tr>
</tbody>
</table>

Table II  Fiber properties of the Norway spruce samples.

<table>
<thead>
<tr>
<th></th>
<th>Slow-growth</th>
<th>Fast-growth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sap</td>
<td>Heart</td>
</tr>
<tr>
<td>Length w. av. fiber length, mm *</td>
<td>3.4</td>
<td>3.0</td>
</tr>
<tr>
<td>Mean fiber wall thickness, µm **</td>
<td>3.9</td>
<td>3.1</td>
</tr>
<tr>
<td>Mean fiber wall thickness, µm *</td>
<td>5.7</td>
<td>5.3</td>
</tr>
<tr>
<td>Proportion of latewood fibers, % *</td>
<td>34</td>
<td>28</td>
</tr>
<tr>
<td>Microfibril angle, ° **</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

* Values determined from the sample discs from the top end of the bottom log and from the lower end of the top log, except dry solids content from the chips.

** Macerated fibers

SilviScan

Compared to the fast-growth wood samples the slow-growth samples had higher density, higher latewood content, higher average fiber length and higher fiber wall thickness (also wider distribution), and lower microfibril angle of the S2 layer of the fiber wall (narrower distribution) (Figures 1-3). In both stem types, the sapwood samples had the highest fiber length and fiber wall thickness, highest latewood content and the lowest microfibril angle.

All the measured wood properties are clearly related to each other. High density means higher fiber dimensions and higher latewood content, but also low microfibril angle. The fast-growth sapwood sample is the one differing most of this pattern. For a low-density wood it has rather high fiber dimensions, although the latewood content is low.
Figure 1. Wood density and fiber length of the Norway spruce wood samples.

Figure 2. Fiber wall thickness distributions (SilviScan, mass-weighted) of the Norway spruce wood samples.

Figure 3. Microfibril angle distributions (SilviScan, mass-weighted) of the Norway spruce wood samples.

REFINING AND PULP TESTING

The pilot refining trials were performed with KCL’s RGP 44 refiner. Ca. 600 kg o.d. chips per wood sample were used for the trials. Half of the both heartwood chip lots were refined in their original dry solids content, and the other half was water impregnated in the digester (4 m³). The refining conditions are presented in Table III.
Table III  Refining conditions of the pilot TMP trials.

<table>
<thead>
<tr>
<th>Refiner</th>
<th>KCL RGP 44</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defreezing of the chips</td>
<td>5 min steaming</td>
</tr>
<tr>
<td>Water impregnation of the heartwood chips</td>
<td>15 min steaming + 30 min water impregnation with cold water</td>
</tr>
<tr>
<td>Refining mode</td>
<td>SD</td>
</tr>
<tr>
<td>Preheating pressure and time, 1st stage</td>
<td>100 kPa, 43 s</td>
</tr>
<tr>
<td>Rotation speed</td>
<td>1500 rpm</td>
</tr>
<tr>
<td>Refining pressure, 1st / 2nd and 3rd stage</td>
<td>300 kPa / 150 kPa</td>
</tr>
<tr>
<td>Outlet consistency target</td>
<td>30%</td>
</tr>
</tbody>
</table>

The pulp samples were hot disintegrated and tested according to ISO standards and methods used at KCL. The paper technical properties were determined from 60 g/m² laboratory sheets made with circulated white water.

**BEHAVIOR OF WOOD FIBERS IN THE REFINING PROCESS**

The fiber wall thickness seemed to be more significant factor affecting the specific energy consumption than the wood density (Fig. 4a). The energy consumption of the fast-growth sapwood was at almost as low level as that of the slow-growth wood samples.

The fiber length of the pulp samples correlated with the original length of the wood fiber (Fig. 4b). Percentually the fast-growth heartwood and top log pulps retained their fiber length best. They had clearly smaller proportion of long fibers, and somewhat higher proportion of other fiber fractions, also fines. The differences in the fines content were rather small, max 4% units. Water impregnation of the heartwood before refining increased the fiber length at low freeness levels, but only in the case of slow-growth wood.

Fiber wall thickness was measured from the long fiber fractions (McNett >28) of the TMP samples using light microscopy. The slow-growth sapwood pulps had clearly the thickest fiber walls (mean value) and the fast-growth heartwood and top log pulps had the thinnest fiber walls, as was the case already for the virgin wood fiber. Fiber wall of the sapwood fibers gets thinner somewhat faster than fiber wall of the heartwood or top log fibers. The clear differences in the shape of the mass-weighted distributions of slow-growth sapwood and fast-growth heartwood were preserved even after three refining stages (Fig. 5).
The splitting tendency of the fibers (McNett >28) was studied by light microscopy method along the fiber length. The number of the intact fibers after 1st and 2nd refining stage was the highest for the thin-walled TMP fibers made of fast-growth heartwood and top log wood, but the decrease through the process was also the fastest. These fibers were the least split (Fig. 6). The sapwood pulps had it vice versa: the lowest proportion of intact fibers and the highest proportion of split fibers. The 3rd stage fast-growth sapwood fibers were the most split.

It is known that thin-walled early wood fibers have higher risk of being split than thick-walled latewood fibers /8/. That was seen also in these studies. However, the fibers from the wood raw materials with higher average fiber wall thickness were more split than the on average thinner-walled fibers. It can be speculated that the fiber material influences the defibration action.
Figure 7. a) Specific filtration resistance (McNett 48/200) and b) specific sedimentation volume (McNett <200) as a function of specific energy consumption in TMP refining. ■/□ slow/fast-growth sapwood, ●/○ slow/fast-growth heartwood, ▲/∆ slow/fast-growth top log, “other wood samples”.

The pore volume distribution was measured (by thermoporosimetry) from long and middle fiber fractions of the selected first and third stage TMP pulps. Any fiber fraction from the third stage pulp had higher pore volume than that of the corresponding first stage pulp (Fig. 8). This is in accordance with earlier studies by Maloney /9/. The growth was small compared to the change after the first stage refining. The only noticeable differences between the different wood samples were in the middle fractions: the middle fractions of the slow-growth sapwood TMPs were more porous than that of the fast-growth heartwood TMPs. The result is congruent to the results of the specific filtration resistance measurements of the same fiber fraction.

Figure 8. Development of the pore volume (measured using thermoporosimetry) from wood to different TMP fiber fractions in 1st and 3rd refining stage. ew – early wood, lw – latewood, S – sapwood, H – heartwood.

CREATING NEW ENERGY – PROPERTY COMBINATIONS

The paper technical properties of the TMP samples showed that by selection of Norway spruce wood raw material very different TMP energy - property combinations are possible to produce.

All the pulps made of thick-walled wood raw materials had good tensile index (Fig. 9a). Only the thin-walled fast-growth heartwood and top log pulps had tensile index in a lower level. Tear index correlated with the original fiber length of the wood samples within the growth rate type (Fig. 9b) being the best for the slow-growth sapwood pulps. The other thick-walled long fiber pulps (slow heart and top, and fast sap) were in the same rather good level, and the fast-growth heartwood and top log pulps again in the lowest level.
The fast-growth heartwood pulps had the highest opacity and light scattering coefficient (Fig. 10a). Due to the less bonding middle fraction and fines material, also the other fast-growth pulps had higher values than the comparable slow-growth pulps. The light scattering – tensile variation between the pulps made of different wood samples is remarkably large. For example, at the light scattering level 60 m²/kg tensile index varies from 32 Nm/g to 56 Nm/g. Even just for the top log pulps the difference between the slow and fast-growth pulps is 10 units in both tensile and scattering (at the scattering level 60 m²/kg or at the tensile level 45 Nm/g).

The fast-growth sapwood had the highest brightness and the slow-growth heartwood the lowest (Fig. 10b). The fast-growth pulps had higher brightness than slow-growth pulps. The heartwood samples had the highest light absorption coefficient.

DISCUSSION

The results show the large differences in the wood fiber property distributions between different wood lots. Except for fiber length distributions mainly average values have been used for other fiber properties in earlier studies. Improved and faster methods are required to produce reliable and good quality data in order to replace the mean values with the distributions.

An interesting contradiction to earlier studies was that the thick walled raw material seemed to split more than thin walled raw material. The earlier results have been obtained when the properties of thin and thick walled fibers were
analyzed as separate groups, while in these studies the whole raw material lots were compared. Usually high number of split fibers is also related to flake like poorly bonding fines material. In this case however, fibrillar well bonding fines material is formed from slowly grown and thick-walled fibers, which is also a typical feature of thick walled fibers. These contradictions could be influenced both by the wide property distributions and the interactions between the wood fiber material and defibration action. Thick walled fibers may form a less compressible fiber bed between the plates and thus receive harsher impacts while the thin walled fibers form a more compressible fiber bed which could also react to the passing bars by compressing and decompressing.

It is well known that fiber length has clear effect on tear strength, and the bonding ability of different fiber fractions influences the strength properties and optical properties. Less energy is required to produce more fibrillated and better bonding particles from the thick-walled fibers. Thin, flexible fibers create high specific surface, more small fiber fractions with low bonding ability but better light-scattering.

**CONCLUSIONS**

The behavior of wood in mechanical processing cannot be predicted just by the growth rate or density. The fiber dimensions explain a major part of the results, but also the fiber wall structure and how it interacts with the defibration action has an effect. Mean values are not often enough to explain the behavior, but also the fiber property distributions should be known better.

By selecting Norway spruce wood raw material by the growth rate and the position in the stem the energy-property combinations of TMP can be greatly influenced.

- The energy consumption at certain freeness level in TMP refining is affected mainly by the fiber wall thickness. Using slow-growth wood or sapwood of the fast-growth wood the energy consumption can be reduced.
- Good strength properties with low energy consumption can be achieved by using wood-raw material with thick-walled and long fibers – slow-growth wood or sapwood. The slow-growth sapwood gives especially high tear index.
- The best raw material for high opacity and light scattering is the fast-growth heartwood with thin-walled fibers. Also the fast-growth top log gives good optical properties when compared at the same tensile.
- The fast-growth sapwood had the best brightness potential, and that is simultaneously with good strength properties.

**ACKNOWLEDGEMENTS**

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Outline

• Objective
• Wood raw material
• TMP trials
• Behavior of wood fibers in the refining process
• New energy – property combinations
• Conclusions
Objective

The current study was designed to relate the pulp fiber properties to various wood fiber properties (Norway spruce) in order to find alternative energy – property combinations for mechanical pulping.
Wood raw material
Selection of wood raw material

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<td>Heartwood cont., area w., %</td>
<td>50</td>
<td>29</td>
</tr>
</tbody>
</table>

* Average ages of the trees 99 and 30 years.

Dry solids content:
- sap and top 38-43%
- heart 62-68%
Wood handling
Slow-growth wood has higher density and longer fibers
Significant differences in the fiber wall thickness distributions

* SilviScan data, mass-weighted
Slow-growth wood has higher proportion of latewood fibers

* Macerated wood samples
Significant differences in the microfibril angle distributions

*SilviScan data, mass-weighted*
TMP trials
Refining conditions

- Chip presteaming: 5 min (defreezing) or
- Heartwood moistening: 15 min steaming + ½ h water impregnation

**REFINER STATION**

**RGP 44**

- Preheating pressure: 1st stage 100 kPa

**SD refining in 3 stages**
- Rotating speed: 1500 rpm
- Refining pressure: 1st stage 300 kPa, 2nd and 3rd stage 150 kPa
- Output consistency 30%
Wood raw material with thick-walled fibers has low energy consumption.

![Graph showing the relationship between CSF (ml) and SEC (MWh/t) for fast-growth sap, fast-growth heart and top, and slow-growth wood types.]
Behavior of wood fibers in the refining process
Thin-walled fibers retained their original fiber length best

- 3rd stage TMP, SEC 3.3-3.9 MWh/t, CSF 31-90 ml
Thick walled raw materials were more split.

![Graph showing split fibers percentage against fiber wall thickness]
Differences in the shape of the fiber wall thickness distributions were preserved.
Low bonding fines and middle fraction from the thin-walled fibers
Pore volume of various raw materials developed differently

The diagram shows the pore volume of different raw materials plotted against pore size (nm) and SEC MWh/t. The materials include slow-growth sapwood with long fibers, middle fraction, and slow sap, fast sap, fast heart, and long fibers. Each material type is represented by different lines and markers, indicating the cumulative pore volume (ml) across various pore sizes.
New energy – property combinations
Long- and thick-walled fibers gave good strength properties.
Fast grown wood raw materials gave good optical properties.
Conclusions 1: Behavior of wood fibers in the refining process

- The behavior of wood in mechanical processing cannot be predicted just by the growth rate or density.
- The fiber dimensions explain a major part of the results.
- Also the fiber wall structure and how it interacts with the defibration action has a significant effect.
- Not only the mean values, but also the fiber property distributions should be known better.
Conclusions 2: Creating new energy – property combinations

- Thick-walled raw material, slow-growth wood or sapwood of the fast-growth wood, gave lower SEC vs. CSF than thin-walled fibers.
- All thick-walled fibers gave good strength properties.
- Thick-walled and long slow-growth sapwood fibers gave the highest tear index.
- The best opacity and light scattering were given by the fast-growth heartwood.
- The fast-growth sapwood gave the best brightness, and that is simultaneously with good strength properties.
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