An industrial evaluation of a stand level grading system for

*Pinus patula*

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Abstract

This paper reports on progress made in the development and implementation of a stand level wood quality grading system for *P. patula* identified for processing in Mondi Merebank’s stone ground wood and thermo-mechanical pulp lines. The grading system stratified the resource using fibre collapsibility as the selection criteria.

The paper evaluates the impact of the grading system on the process parameters and the basic characteristics of pulp produced by the different pulp lines. The grading system was found to have a positive impact on desired pulp quality criteria.

Variability inherent in the resource and the production process declined significantly upon implementation of the grading system. The results indicate the level of improvement that can be realized from a simple wood quality grading system. It is anticipated that a more detailed understanding of factors impacting on wood and pulp characteristics, and resource and process variation will support a process of continuous pulp quality improvement.

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1. Introduction

Mondi Merebank pulp and paper mill, a producer of thermo mechanical pulp (TMP) and stone ground wood (SGW) pulp identified a need to improve its understanding of the quality of the wood resource entering the pulp mill. This was driven by the need to determine whether it was possible to manage wood quality entering the mill in order to control both the strength and variability of its pulp characteristics. During this process, the CSIR was asked to help address this issue.


The wood resource entering the pulp mill was almost entirely *Pinus patula*. Prior to the start of this process, a grading system based on the age of timber had been tested at the mill and was found to have no significant impact on pulp quality. The effect of environment and growth rate had not been considered in this grading system. It is known that the rate of growth has a fundamental impact on anatomical properties (Wang and Braaten 1997, Hosseini 1991).

From an understanding of the key pulp quality issues and prior research knowledge, consensus was reached between Mondi Forests fibre logistics team, pulp mill technical staff and CSIR scientists that a study of the impact of age and site quality (growth rate) on anatomical characteristics of the material entering the mill was required. The goal was to increase our knowledge of the variation within the resource, which would then be used to stratify the resource to meet different pulping process requirements.

For the purposes of the investigation an assumption was made that the SGW process was more sensitive to variation in wood characteristics than the TMP process. The TMP process is generally considered to be the more sophisticated and robust. Fibre collapsibility was identified to be of most importance in the SGW defibration process. For example, thick walled, small diameter cells offer fibres of low collapsibility, which tend to produce a poor quality SGW pulp with a high proportion of shives. It was concluded that in any grading system, the SGW process would be the key focus point with the TMP process being regarded as subordinate within the grading process.

2. Methodology

The project design involved the evaluation of wood properties of *Pinus patula* at the oldest available age from three different site qualities (low, medium, and high growth rates). The two greatest extremes of site quality were selected to ensure that the full extent of variation entering the mill would be captured. A conscious decision was taken to select material from similar stocking levels and altitudes. An average elevation was taken for all sites to try and capture material that was as representative as possible of the
total resource. The decision was taken with the understanding that if this preliminary grading system was successful then the study would be extended in future to include altitude and stocking levels as addition variables over a similar site index range.

2.1 Field sampling

The sampling phase initially began in June 1998 and finished in August 1998. Stands were selected and sampled after a rigorous study of available compartments from all the major suppliers of timber to Mondi Merebank.

Once a site had been identified as a potential candidate, a micro site of the compartment was selected for relative homogeneity in the area where trees were to be sampled. A 6% enumeration from the micro site area was used to confirm that the area complied with one of the three site categories (high, medium and low growth rate). The other information used to determine the overall suitability of each site as a representative sample per site quality is listed in Table 1.

Table 1. Information on the three compartments identified for destructive sampling

<table>
<thead>
<tr>
<th>Site Quality (growth rate)</th>
<th>Age at Time of Sampling</th>
<th>Measured MAI (m³/yr)</th>
<th>Site Index (at age 20)</th>
<th>Thinning Age</th>
<th>SPH</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>30</td>
<td>25.3</td>
<td>25.3</td>
<td>13</td>
<td>707</td>
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<td>Medium</td>
<td>34</td>
<td>17.7</td>
<td>21.3</td>
<td>12</td>
<td>611</td>
<td>1250m</td>
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<tr>
<td>Low</td>
<td>26</td>
<td>11.5</td>
<td>17.2</td>
<td>14</td>
<td>726</td>
<td>1100m</td>
</tr>
</tbody>
</table>

Once the sites had been confirmed as suitable, a random selection of 10 trees was sampled within the micro sites identified. Their DBH’s were measured and felling commenced. After felling, total tree heights and tree bole taper were measured at 3 metre intervals from the base of the tree. Destructive sampling locations were marked at breast height, 35% and 65% of total tree height (Figure 1). 25cm thick disks were taken at each of the designated heights.

2.2 Anatomical analysis

From each of the destructively sampled discs taken up the tree, a strip was cut from the pith to the bark. The strip was cut in two parts, one for anatomical characteristics and the other for ring width measurements (Figure 1). At breast height, rings 4, 6, 8, 12, 18 and 25 were measured to determine the range and mean of anatomical properties from pith to bark. At 35 and 65% of total tree height, the rings were counted from the bark to ensure that the measurements were carried out in the same rings at different heights. From the strips earmarked for anatomical analysis, cubes of wood were cut at the demarcated growth rings. The surface of the cubes was cut with a microtome until a smooth surface was obtained. In each ring, the measurement was carried out separately in both late wood and early wood. Wood characteristics measured included fibre diameter, lumen diameter...
and fibre wall thickness. Measurements were carried out using a research microscope with fluorescence light and a Kontron image analysis system.

In order to translate measurements into a meaningful value, anatomical values were then converted into collapsibility values using equation 1 which was adapted from the equation for collapsibility of a pipe. Collapsibility is a ratio that determines the ability of the fibre to defibrate without being destroyed and to subsequently flatten in the paper sheet. Higher values reflect more collapsible material.

**Equation 1: Collapsibility**

\[
\text{Collapsibility} = \left[ \frac{3 \times \text{Cell diameter} + 5 \times \text{Wall thickness}}{(\text{Wall thickness})^2} \right]
\]

**Figure 1. Sampling for anatomy and ring width measurements**

2.3. Fibre length measurements

From each of the identified growth rings a representative piece of wood was isolated. This sample was placed in small test tube and macerated by adding a mixture of glacial acetic acid and hydrogen peroxide. The test tubes were left for 48 hours in an oven at 60°C, after which, the maceration was diluted with water. One drop of the diluted pulp from each tube was placed on a microscope slide, which was then dried on a hotplate. The fibre length measurement was carried out with a binocular microscope, a digital table and an image analysis system.
2.4. Ring width measurements

From each ring width sample a photocopy was made (Figure 2) which was then differentiated into early wood and late wood. On Figure 3a, the image analysis measured the late wood width; on 3b it measured early wood. After measuring the photocopy, the image analysis system converted the image to an early wood/late ratio.

Figure 2. Photocopy of strip scanned with video camera

![Figure 2](image)

Figure 3. Black and white image. 3a for measurement of late wood width, 3b for measurement of early wood width

![Figure 3](image)

3. Results of anatomical measurements

Figures 4, 6, 8 and 10 show the observed trends in cell diameter, wall thickness and fibre length (at breast height) with age for the three site types. For the same set of anatomical characteristics, Figures 5, 7, 9 and 11 show the mean of whole tree values for three different ages. The letters in these graphs indicate where significant differences occur between sites (as determined by a Duncan test).

Figures 12 and 13 are summary graphs of the impact of age and site quality on cell diameter, wall thickness and collapsibility.
Figure 4. Variability of cell diameter of *Pinus patula* with age for low, medium and high sites.

![Variability of cell diameter of Pinus patula with age for low, medium and high sites.](image)

Figure 5. Mean of cell diameter and 95% confidence intervals. The letters indicate where significant differences occur between sites (Duncan test).

![Mean of cell diameter and 95% confidence intervals.](image)
Figure 6. Variability of lumen diameter of *Pinus patula* with age for low, medium and high sites.

![Graph showing variability of lumen diameter with age](image)

Figure 7. Mean of lumen diameter and 95% confidence intervals. The letters indicate where significant differences occur between sites (Duncan test)

![Mean of lumen diameter at BH graph](image)
Figure 8. Variability of wall thickness of *Pinus patula* with age for low, medium and high sites.

![Graph showing variability of wall thickness with age for low, medium, and high sites.](image)

Weigthed mean of wall thickness at BH

![Graph showing weighted mean of wall thickness at BH.](image)

\[ y = 0.0391x + 4.5372 \]

\[ R^2 = 0.9434 \]

Figure 9. Mean of wall thickness and 95% confidence intervals. The letters indicate where significant differences occur between sites (Duncan test).

![Graphs showing wall thickness at 12, 18, and 25 years for low, medium, and high sites.](image)
Figure 10. Variability of fibre length of *Pinus patula* with age for low, medium and high sites.

Figure 11. Mean of fibre length and 95% confidence intervals. The letters indicate where significant differences occur between sites (Duncan test).
Figure 12. A summary of the impact of age on anatomical properties (*Pinus patula*)

The cell diameter, lumen fibre diameter, and fibre length increase with age until 12 years. After 12 years these properties become stable (the variability decreases). Wall thickness increases continuously with age. After 12 years, cell diameter does not increase and wall thickness continues to increase. Collapsibility decreases due to this anatomical relationship.

Figure 13. A summary of the impact of site on anatomical properties (18 years old *Pinus patula*)

Cell diameter, lumen diameter and fibre length increase when site quality increases. There is no impact of site quality on wall thickness. An increasing site quality increases only cell diameter: Collapsibility will be higher. Trees from the better sites have the most collapsible material.
4. Kriging

The results from the variance analysis to identify the variability of wood properties within tree are difficult to conceptualise. There are variations in the trends of some anatomical properties from BH to 65% height, by age and site quality. This shows that any attempt to model within tree variation between sites will need to account for age and site quality as well as height in the tree.

Once the anatomical characteristics of the trees had been determined, an overall analysis of fibre collapsibility within trees was determined using a spatial statistical technique known as Kriging. Kriging is a form of weighted spatial averaging; the influence a point has on neighbouring points is determined by the distance between them (Holmgren et al. 1997). Modelling using Kriging techniques permits an intuitive visualisation of trends through the mapping of tree fibre qualities.

Wood anatomical data is inherently auto correlated due to the samples being taken from within the same tree. This auto correlation causes traditional statistics, which assume independent samples and normality, to be invalid with this type of analysis. Kriging, a spatial statistical method, does not make these assumptions but instead assumes no systematic change in values in any particular direction (ESRI, 1996).

Averages of anatomical measurements were derived from the 10 Pinus patula trees from 3 sites across three different ages. The age (determined from growth rings) and percent height of the tree were noted during the image analysis. Growth models were used to convert percent heights into heights in metres (Y) and growth rings into radius distance in centimetres (X). These coordinates, along with the anatomical data, were loaded into a Geographic Information System (GIS) for analysis and the collapsibility function was modelled (Figure 15).

The models were run in GRID within ArcInfo (ESRI, 1996). Once analysis of the data had been completed the information was exported as a polygon coverage and a point coverage for further analysis. Data within the polygon coverage was grouped to show significant trends throughout the inside of the tree. The point coverage contained the modelled wood quality values along with the point locations of each modelled point. Total volumes (TV) were determined using (height of pixel) * p * (radius from centre of tree). Volumes per pixel (PV) were then determined using TV \[ n \] - TV \[ (n-1) \] where \( n \) is the distance from the centre of the tree. Weights, per characteristic, were calculated by PV/PV\[ min \] for each pixel where min is the minimum pixel volume (centre of the tree). The wood quality value was then multiplied by the weight to obtain a weighted wood quality value. Mean wood quality value per bucking log was determined using \( \text{mean wood quality per bucking log} = \left( \frac{\sum \text{weighted values per pixel per bucking log}}{\sum \text{weights per bucking log}} \right) \).

All information was converted to ArcView to generate collapsibility maps (Figure 15). Mean collapsibility values were then linked to the bucking logs. Different categories (colours) for the collapsibility maps are based on significant differences in the data from
the point sampling. The values represented in the discussion (section 6) are those from the weighted mean of individual logs and the range in the data.

Figure 15. Map of Collapsibility values for different sites and ages

Tree Height (2.5 m bucking log)

Tree Radius (cm)

Legend
Collapsibility
< 4.5
4.5 - 5.5
> 5.5

Sites were defined:
Low Site - MAI 12
Medium Site - MAI 18
High Site - MAI 25
All surfaces were interpolated using sampling data obtained during winter 1998. Sampling data were averaged over 10 trees per site type.

Map date: 15 February, 1999

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Dr. Michael St ,[ et al. ]
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5. Using the outputs from Kriging to model site/age interaction

Using the outputs from Kriging, two collapsibility models were developed. The models were used to develop a grading procedure that could translate information into collapsibility values across a range of site qualities and ages contained within a typical plantation database. The first was a stand level model, which was based on mean annual increment and age. The second was a model to evaluate characteristics up the tree in 2.5 m (pulp log) intervals.

5.1 Mean annual increment/age models

The first model uses MAI and age (Equation 2) to determine collapsibility at a stand level. This model was developed to utilize the most common measure of site available from forest planning records. The regression for the model is found in Figure 16. The model indicates a decreasing collapsibility with increasing age and decreasing MAI.

Equation 2: Equation for MAI and Age modeling for Collapsibility ($R^2 = 0.93$).

\[
COLLAPSIBILITY = b_0 + b_1 \cdot \text{Age}^{-1} + \frac{b_2}{\ln MAI}
\]

where:

- $B_i =$ coefficients
- $MAI =$ Mean Annual Increment

Figure 16. MAI and Age model for collapsibility
5.2 MAI with tree height models (2.5m logs)

A second model was developed to determine within tree variation while also applying age and MAI measures (Equation 3). Figure 17 shows three different MAI classes with the collapsibility within a tree at 2.5m log sections. Collapsibility decreases with increasing age, and decreasing MAI. The model shows increasing collapsibility as one selects logs further up the tree. This function was developed to help determine whether within tree sorting would increase the collapsibility of the total resource for the SGW line. The base logs of the stands being considered for log sorting had higher collapsibility values than the alternative stands being considered for volume replacement. Since the alternative resource being considered to replace the volume of the butt logs was less collapsible than the butt logs, the option to implement a bucking system to differentiate between logs was not taken.

Equation 3. Equation used in regression for Collapsibility using Age, Height up tree and MAI ($R^2 = 0.83$)

\[
\text{COLLAPSIBILITY} = b_0 + b_1 \cdot \text{AGE}^{-1} + b_2 \cdot \ln \text{LHT} + \frac{b_3}{\ln \text{MAI}}
\]

where:

- $B_x =$ coefficients
- $LHT =$ Log · Height · (2.5m · bolts)
Figure 17. Collapsibility Modeled for Individual Tree Ages by MAI
6. Discussion of variability of wood characteristics with age and site quality

The cell diameter (Figure 4) and lumen diameter (Figure 6) increase from the pith until the tree has reached 12 years old for the 3 sites. After this, cell diameter and lumen diameter are stable for the low site, and decrease for the medium and good site.

Wall thickness increases with increasing age for the 3 sites (Figure 8). Site quality does not significantly impact on this property (Figure 9).

Fibre length increases with increasing age (Figure 10) and with site quality (Figure 11).

The trends in the data indicate that site quality plays a vital role in the transition period of anatomical characteristics. Some characteristics, cell diameter and lumen diameter have different ages for peaking, and different range and amplitudes for the values. Other values have longer transition periods (fibre length) with a higher error variance between sites. Wall thickness shows no differences between sites as only age is influential.

It may be concluded that variation in the data is not wholly captured by concepts such as juvenile wood. This highlights the importance of using real measures when stratifying the resource.

There was a general trend that collapsibility increased with site quality and decreased with age. The collapsibility ratio shows that the highest values occur in the centres of the trees throughout all three sites. The lowest collapsibility values occur along the outsides of the trees. The high site produces the most collapsible material (ranged 5.01-5.81 mean weighted values) whereas the low site produces the least (4.74-5.20). The medium site had the most variability and ranged from 4.73 to 6.00.

These results showed that most of the variability of wood quality properties occur within a tree as opposed to between the sites for *Pinus patula*.

7. Pulp mill trial

The total fibre source entering Mondi Merebank was identified from the plantation database. Using the MAI and age information, each compartment was graded for collapsibility and the 40% most collapsible material identified as SGW material. This information was then used by the logistics manager who then liaised with harvest scheduling and transport personnel to ensure that an even stratification of SGW and TMP material was despatched to the mill.

In order to determine the benefit of using the collapsibility scheme, a number of resource and pulp quality variables normally captured during the pulping process were gathered prior to implementation of the pulp mill trial to capture a control data set. This period of control data recovery lasted from 10 May 1999 to 30 September 1999. The test period for the graded material entering the mill for the trial period was from 1 October 1999 to 30 November 1999.
With both a 5-month benchmark data set and a two-month trial data set, the stone ground wood process was evaluated for improvements. At the same time, the TMP lines were evaluated to identify any changes that might occur in this process. Variables measured during the trial are summarized in Table 2.

The overall goal was to increase collapsibility of the fibre. Since there was no direct measure of collapsibility in the mill, indirect measures were identified and evaluated. The production of shives was considered to be an important measure. Shives are “bundles” of fibres. Since the fibre complex is more likely to break and collapse in the high collapsibility stands selected for the SGW line, there should theoretically have been less shives during the trial period.

Rejects that are subsequently sent through the reject refiner are due to incomplete breakdown of the fibre complex. On this basis, a decrease in rejects should be observable. A new, more sensitive variable referred to as special rejects was developed from the existing measures. This value was a ratio of the rate of production over the rate of rejects. With a more collapsible fibre, less fibre should be diverted to the reject refiners. A hypothesis was set that “special rejects” should increase during the trial period if collapsibility increased.

After supplying the needs of the stone ground wood line from the young, fast growing sites, the TMP process was destined to receive the remainder of the fibre resource. It was difficult to predict in absolute terms the impact on pulp and process characteristics. However, having removed 40% of the most collapsible material, a significant reduction in variability was expected.

Tests used to compare the trial period with the benchmark data set included comparison tests on the means and the variability of the data. The key findings of the two data sets are summarised in Table 3.
Table 2. List of Measures for the stone ground wood and thermo-mechanical pulp lines.

<table>
<thead>
<tr>
<th>Process</th>
<th>Area</th>
<th>Measurement</th>
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</thead>
<tbody>
<tr>
<td>SGW line</td>
<td>Saw Deck</td>
<td>Timber Moisture</td>
</tr>
<tr>
<td></td>
<td>Grinders</td>
<td>Consistency</td>
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<tr>
<td></td>
<td></td>
<td>Freeness</td>
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<tr>
<td></td>
<td></td>
<td>Tensile</td>
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<td></td>
<td></td>
<td>Tear</td>
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<tr>
<td></td>
<td>Decker-SGW</td>
<td>Porosity</td>
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<td></td>
<td>Brightness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Freeness</td>
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<tr>
<td></td>
<td></td>
<td>% Shives</td>
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<tr>
<td></td>
<td></td>
<td>Bauer McNett’s</td>
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<tr>
<td></td>
<td></td>
<td>Tensile</td>
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<td></td>
<td>Tear</td>
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<td></td>
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<td>Apparent Density</td>
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<td>Opacity (light scattering)</td>
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<td></td>
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<td>SSC (light scattering)</td>
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<td>Process</td>
<td>Variables</td>
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<td>Reject Refiner Load</td>
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<td>% Shives</td>
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<td>Process</td>
<td>Variables</td>
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<td>Reject Specific Energy</td>
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<td></td>
<td>Specific Energy</td>
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<td></td>
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<td>Reject Rate</td>
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8. Results of the pulp mill study

Table 3. Summary of important significant differences from the pulp mill study

<table>
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<tr>
<th>Stone ground wood process</th>
<th>MEAN</th>
<th>DATA VARIATION</th>
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</thead>
<tbody>
<tr>
<td>Screen Rejects</td>
<td>Control (30%)</td>
<td>Control (103%)</td>
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<tr>
<td>Reject Ratio</td>
<td>Control (4%)</td>
<td>Control (103%)</td>
</tr>
<tr>
<td>Specific Energy</td>
<td>Trial (2%)</td>
<td>Control (160%)</td>
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<tr>
<td>Production</td>
<td>Trial (1%)</td>
<td>Control (118%)</td>
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<tr>
<td>Special Re Rejects</td>
<td>Trial (22%)</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>Control (20%)</td>
<td>Control (120%)</td>
</tr>
<tr>
<td>Density</td>
<td>Trial (3%)</td>
<td>Control (170%)</td>
</tr>
<tr>
<td>Tensile</td>
<td>Trial (3%)</td>
<td>Control (150%)</td>
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<tr>
<td>Tear Index</td>
<td>Trial (7%)</td>
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<tr>
<td>Shives%</td>
<td>Control (21%)</td>
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<table>
<thead>
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<th>Thermo-mechanical pulp process</th>
<th>MEAN</th>
<th>DATA VARIATION</th>
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</thead>
<tbody>
<tr>
<td>Tensile</td>
<td>Trial (4%)</td>
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<tr>
<td>Burst</td>
<td>Trial (2%)</td>
<td></td>
</tr>
<tr>
<td>Shives</td>
<td>Trial (7%)</td>
<td>Control (140%)</td>
</tr>
<tr>
<td>Reject Rate</td>
<td>Control (17%)</td>
<td>Control (200%)</td>
</tr>
</tbody>
</table>

Trial / control: denotes the larger significant value with percent difference

Special rejects = product rate / reject rate (high value is better)

Reject ratio = total production / rejects produced (small value is better).
9. Discussion of the pulp mill study

9.1 Stone ground wood

Process variables

Screen rejects were 30% higher and 103% more variable in the control data set. According to our hypothesis, this indicates that the grade of logs entering the mill had significantly more collapsible fibre. When taking into account production rate over reject rate (special rejects), this “corrected” reject rate dropped to 22%. This was considered the most representative measure of the improved collapsibility of the trial fibre.

It was noted that specific energy requirements were slightly higher in the trial (2%). Some of this could be ascribed to the higher production rate. The more interesting factor was the substantially higher variation in energy consumption (160%) during the control period. This offers a clear indication that the material entering the mill was more consistent in the trial.

Pulp properties

Pulp porosity was significantly higher and more variable in the control period. This was thought to be due to the inclusion of a greater number of longer, coarser fibres associated with more mature wood that was specifically excluded in the trial period.

It was encouraging to observe that bulk density, tensile and tear all improved significantly during the trial. In addition, there were significant and very substantial decreases in variation for density and tensile compared to the control.

As predicted, the percentage shives in the pulp was higher during the control period.

9.2 Thermo-mechanical pulp

The grading system during the trial period was designed to improve the characteristics of the stone ground wood process. It was therefore encouraging to note that there were no significant negative influences on the TMP process during the trial.

It was interesting to note that tensile and burst increased significantly and that the reject rate also declined during the trial period. The reasons for these results are not fully understood, but it is thought that at least some of the improvements could be ascribed to a more uniform resource during the trial.

The most informative results were related to variation. The percentage shives and reject rate were significantly and substantially lower in variation during the trial.
10. Conclusions

The trial was considered to be extremely successful in demonstrating the potential gain that can be made through effective grading and stratification of the forest resource entering the pulp mill. There were significant improvements in both process and pulp variables. Of more importance was the substantial reduction in variability that can be achieved through improved understanding of sources of variation and their effective management.

The trial has signposted the way forward regarding potential improvements that can be achieved in pulp mill and product performance through the grading and stratification of the forest resource. The next phase of our investigations will focus on three key issues:

- Improving our understanding of the impact of different components of site quality and their impact on wood characteristics,
- Increasing the species range for evaluation,
- Expanding our studies to include chemical pulp mills.

11. References


