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The pulp and paper properties of *Sirex noctilio* infested and fire-damaged thermomechanically pulped, South African grown *Pinus patula*

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Pinus patula is the softwood species most extensively planted in South Africa. However, large portions of these plantings are under threat from *Sirex noctilio* infestation and occasional forest fires. In this exploratory investigation, the effects of tree age, *Sirex noctilio* infestation and fire damage to wood from *Pinus patula* trees on their pulp and paper properties were evaluated. Pulp was produced using the thermomechanical pulping (TMP) process. The energy consumption required to pulp the different pulpwood materials was determined. Pulps were beaten for five different time periods to investigate the development of the fibre properties in response to increasing energy input. Paper properties such as burst, tear strength and breaking length were determined on handsheets manufactured from unbeaten and beaten pulps. Box and line plots and canonical variate analysis biplots were used to statistically analyse the data. It was found that the burst strength of paper produced from healthy trees was significantly higher than that from sirex-infested or fire damaged (burnt) trees. Similarly, the tear strength of paper from healthy and burnt trees was significantly better than from sirex-infested or young trees. No significant differences in breaking length were evident between the pulpwood materials and an increase in beating time did not lead to any improvements. From this study it can be concluded that wood from dead or dying, sirex-infested and young trees produced paper with consistently lower strength properties compared to wood obtained from healthy 12-year-old trees.

Keywords: breaking length, burst index, multivariate biplots, paper strength properties, *Pinus patula*, pulp properties, *Sirex noctilio*, tear index, thermomechanical pulp

Introduction

Pinus patula is the softwood species most extensively planted in South Africa, comprising 332 925 ha or 50.4% of the total softwood area (Anon. 2007). In South Africa, relatively high stocking levels are implemented in *P. patula* pulpwood plantations. It has been described by Wingfield et al. (2008) that the onset of physiological growth stress in the absence of scheduled thinnings not only increases the risk of fire, but also makes the trees more prone to insect and fungal attack. Furthermore, it was predicted by Tribe and Cillié (2004) that *Sirex noctilio* can establish itself wherever its host trees occur within southern Africa. It is known that *S. noctilio* has spread steadily since its first introduction in the Western Cape (Tribe and Cillié 2004) to Greytown in the KwaZulu-Natal Midlands, a distance of c. 1 400 km (Edwards 2006). The perspectives of these authors prompted this work, aimed at establishing some of the possible effects of *S. noctilio* infestation on the *P. patula* pulp and paper properties. In this exploratory investigation the effect of fire damage to trees and age on their pulp and paper properties was also evaluated.

In a previous investigation that dealt with the influence of the same tree factors (variables) on the chemical properties of *P. patula* wood (du Plessis et al. 2008), it was shown that sirex-infected and burnt trees could be successfully utilised as pulpwood. The results also indicated that due to a higher than normal extractives content, South African grown *P. patula* plantation trees should not be harvested younger than the intended rotation age of 12–14 years. The usefulness of a biplot to simultaneously display the various tree variables and their chemical composition was illustrated.

Since the suitability of sirex-infested softwood timber for applications in structural applications is currently being questioned and as this infestation of *P. patula* and other pine species is expected to increase, it is particularly important for the South African pulp and paper industry to know more about the effects on pulpwood. The objective of this study was to establish to what extent pulps from sirex-infested and also fire-damaged trees are fit for use in commercial paper-making operations. This report addresses the pulp quality and paper strength properties such as burst, tear strength, and breaking length of handsheets, using the thermomechanical pulping (TMP) process as reported by du Plessis et al. (2008). Correlation analyses between the different tree factors (classes) as well as pulping and paper properties of these classes were performed and are discussed.

Materials and methods

The experimental procedure followed is outlined in Figure 1.

Material selection

Wood chips from the same five *P. patula* samples on which the chemical analysis was performed previously (du Plessis et al. 2008) were used in this study of pulping and paper properties. Burnt logs were sourced from the log-deck. It is noted from Table 1 that the origin and age of the burnt logs are unknown; however, the sirex-infested and healthy logs' age and origin are well defined.

Experimental methods

Thermomechanical (TMP) pulping is the process by which high-yield pulps are produced from wood chips. These pulps contain a high percentage, normally in the range of 85–90%, of the original wood components (Eriksson 1990, Kelley et al. 2004).

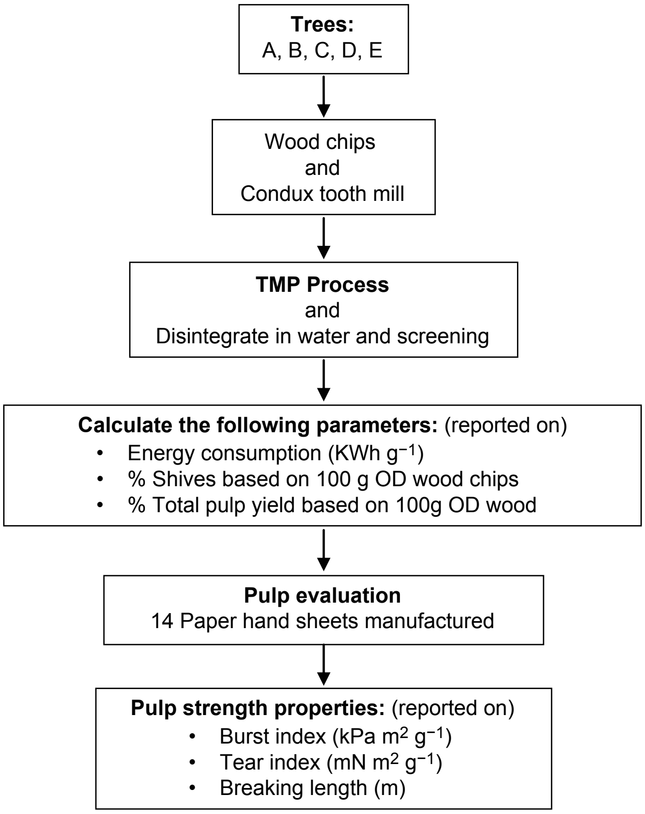

Figure 1: Flow diagram of the experimental pulping study conducted on five different tree classes

Wood chip samples from the five *P. patula* tree classes were first soaked in cold water for 24 h until completely saturated. The TMP process consisted of two phases: wood chips were presteamed with saturated steam (121 ºC and c. 200 kPa) followed by the fiberisation stage that yielded single, loose fibres. A further refining stage (fibrillation) involved the conversion of portions of whole fibres into ribbon-like fibre and cell wall fragments and fibrils, essential for the required bonding properties of paper (Kano et al. 1982). The TM pulp was screened with a 0.2 mm slotted screen and the consistency, percentage shives and pulp yield were determined. Both energy usage (Joules) and duration (seconds) of the TM-pulping process were measured to calculate the energy required (KWh g^{-1}) for each tree class. Pulps of 3.5–4% consistency of each tree class were beaten for 1, 2, 3, 4 or 5 min with a laboratory-scale Voith overhead beater with a basalt lava roll and bed plate.

Fifteen handsheets per tree class were formed, pressed and dried in a Frank sheet former. The one hand sheet with visibly poorest quality was discarded for every tree class. Selected samples were die-cut and conditioned at 20 °C and 55% relative humidity for at least 48 h before strength testing commenced. The burst strength (kPa m^2 g^{-1}) (TAPPI method: T403 om-91), tear strength (mN m^2 g^{-1}) (TAPPI method: T414 om-88) and breaking length (m) (TAPPI method: T404 om-87) were determined on the handsheets, performing 10 repetitive measurements at each point of assessment.

Statistical analysis

As a means of statistical analysis, box and line plots and canonical variate analysis (CVA) biplots were used to scrutinise the data. The CVA biplot methodology was chosen to clearly display differences and overlaps of the properties measured among the different classes. This specific investigation's need was for a CVA biplot to maximise class separation. See van Heerden et al. (2008) and Gardner et al. (2005) for discussions on biplots for pulp and paper applications.

The following information is relevant when considering box and line plots. In this study, separate box-and-whisker plots are drawn for each tree class. Each box-and-whisker plot consists of a box including the inner 50% of the data by extending from the 25th percentile to the 75th percentile with

Table 1: Selection criteria of the experimental material

Class	Status	Description	Features
A	Dead	12 years old; infested by *S. noctilio* for more than two years	Typically a dead crown; bark peeling off at places along the stem. Timber was of low density and at ambient moisture content levels
B	Dying	12 years old; infested by *S. noctilio* for one to two years	Typically needles turning brown; logs still had significant moisture levels
C	Healthy	12 years	Healthy trees at rotation end; regarded as a control
D	Young	Eight years	Healthy trees mid-rotation
E	Burnt	Age and origin unknown	Logs were salvaged from a burnt compartment and kept under irrigation in log deck at the paper mill

the median indicated by a white line. Whiskers are drawn from the box to the minimum value and to the maximum value after exclusion of any outliers in the data. A data point is flagged as an outlier (indicated by a small open circle) when it is more distant from the box than 1.5 times the length of the box. A notch about the median is fitted to each of the box-and-whisker plots, demarcating a distribution free approximate 95% confidence interval for the median (McGill et al. 1978).

Results

Pulping and pulp yield

As shown in Figure 2, the highest median values for pulping energy were obtained for tree classes A (Dead, sirex-infested) and E (Burnt). Notice that a notch (i.e. the confidence interval) can extend beyond the box as is the case with all five box-and-whisker plots in Figure 2. If the notches of two plots do not overlap then the medians are significantly different at the 5% level. Thus the above plot shows strong evidence that the median of tree class A differs from all the class medians except tree class E. The median of tree class E differs significantly from the medians of tree classes B and D since the corresponding notches do not overlap.

When the percentage shives are considered, it is noted that the dying tree class (B) produced the highest percentage (Figure 3). At a 95% level of significance (McGill et al. 1978), the values were higher than the values for the other four tree classes.

Pulp yield is expressed in terms of 100 g oven-dried mass and thus considered as a percentage value. A linear decline in the yield was observed (Figure 4) as examined from the Dead tree class (A), to the Healthy tree class (C), to the Young tree class (D), to the Burnt tree class (E) and ending with the Dying tree class (B). The notch of the latter class does not overlap with classes A, C and D while it overlaps only marginally with the notch associated with tree class E. Noticeable from Figure 4 is the large variation in yield values of the Dead tree class (A).

Strength properties

In Figures 5 to 7 the mean burst strength index, tear strength index and breaking length values are plotted as functions of beating time in minutes for the respective tree classes.

The burst index is an indication of the burst strength per basis weight of paper (Mark et al. 2001). The approximate linear increase of burst index values with an increase in beating time is to be expected and from Figure 5 it is clear that the trends are roughly similar for the five tree classes. Notice also that the behaviour of the Dead (A), Dying (B) and Young (D) tree classes are very similar. The Healthy tree class (C) showed burst strength values (1.36 kPa m^2 g^{-1}), 46% higher that of the Dead trees (Class A; 0.93 kPa m^2 g^{-1}) at the 5 min beating interval.

Tear index is an indication of tear strength per grammage of paper (Mark et al. 2001). Inspection of Figure 6 shows that tear index behaves very much in the same way than the burst index over the 1–5 min beating time range.

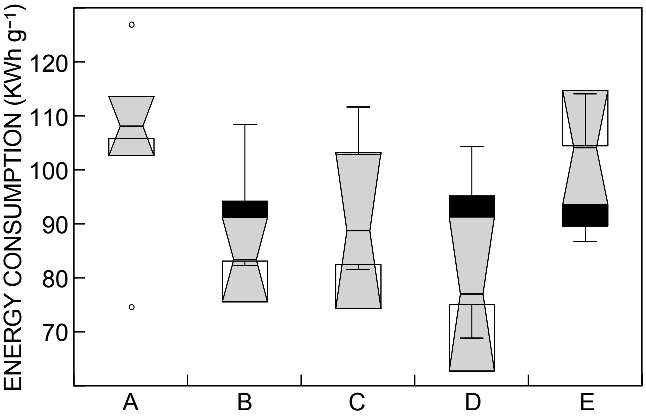

Figure 2: A box-and-whisker plot comparison of the energy consumption per tree class

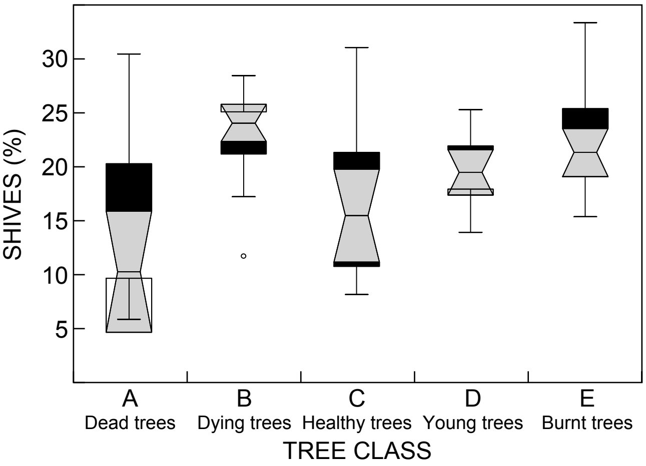

Figure 3: A box-and-whisker plot comparison of the percentage shives per tree class

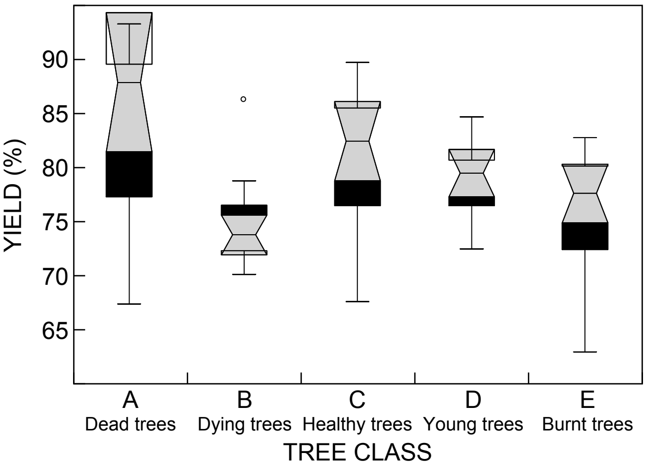

Figure 4: A box-and-whisker plot comparison of the percentage pulp yield per tree class

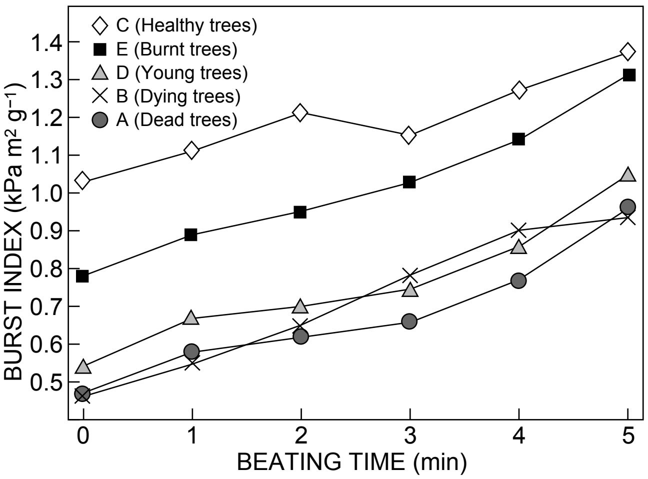

Figure 5: The effect of beating time (min) on the burst index of paper produced from the five tree classes

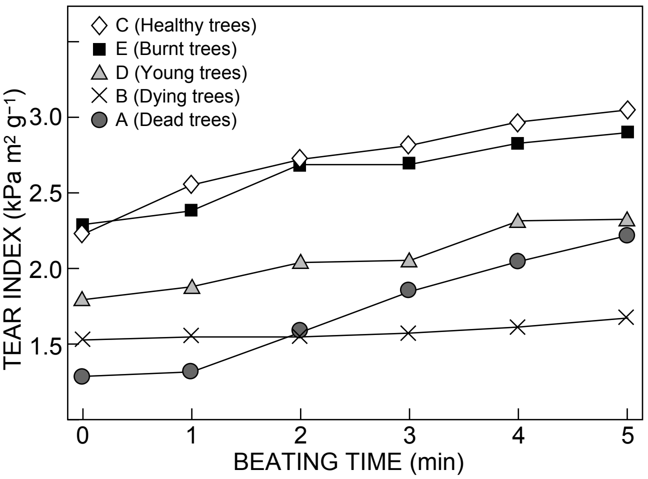

Figure 6: The effect of beating time (min) on the tear index of paper produced from the five tree classes

The Healthy tree class (C) showed tear strength values (3.1 mN m^2 g^{-1}), 82% higher that of the Dying trees (Class B; 1.7 mN m^2 g^{-1}) at the 5 min beating interval. The burst and tear indices approximate a linear increase with increase in beating time.

Healthy (C) and Burnt (E) tree classes had the highest mean values. A notable difference was that beating time could appreciably increase the burst index of the Dead (A) tree class. However at the 5 min beating stage, the mean of the Dead (A) tree class was still below the Healthy tree classes means without any beating.

Contrary to what was found for the tear and burst indices, Figure 7 shows no specific trend in breaking length mean values with an increase in beating time. However, the Healthy (C) and Burnt (E) tree classes had mean values in excess of the other three tree classes at all the respective beating times.

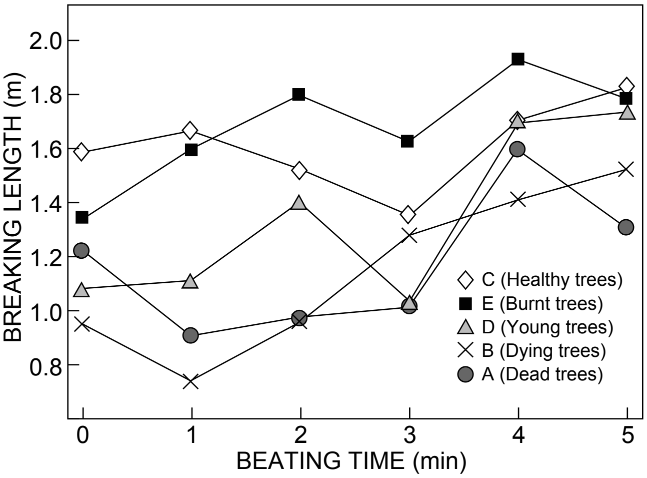

Figure 7: The effect of beating time (min) on the breaking length (m) of paper produced from the five tree classes

Multivariate biplots

In this study four wood chemical properties of the same five tree classes were determined. In typical scatterplots only two properties can be visually displayed at a time. The biplot, introduced by Gabriel (1971) and Gower and Hand (1996), provides a means for displaying, in a single graph, all samples that were used together with all the property information measured for these samples. Although Figures 5 to 7 contain valuable information, these figures do not take the multidimensional nature of the data into account. The biplot shown in Figure 8 is a visual display of the collective differences among the five tree classes with respect to the three strength properties taking the covariance structure of these properties into account.

Summary discussion

The research question put forward by du Plessis et al. (2008) whether pulp yield and associated properties such as energy consumption, burst strength, tear strength and breaking length were affected by *S. noctilio* infestation or fire damage is discussed.

Processing and pulp yield

The energy consumption of the TM-pulping process clearly indicated higher energy requirements to produce pulp from sirex-infested Dead (A) and Burnt (E) trees. The Dead tree class was the only class of which the fibres were completely dehydrated. High energy consumption is associated with the pulping of non-pliable fibres such as present in class A pulpwood and it can be concluded that the 24 h soaking of fibres in water did not fully hydrate these fibres. It is also noticeable from Figures 3 and 4 that the Dead tree class, with a high percentage pulp yield, also had the lowest percentage of shives. These box plots are reciprocals of each other. The significantly lower pulp yield associated with class B (dying trees), can possibly be linked to the high solvent-borne extractive content as described by du Plessis et al. (2008).

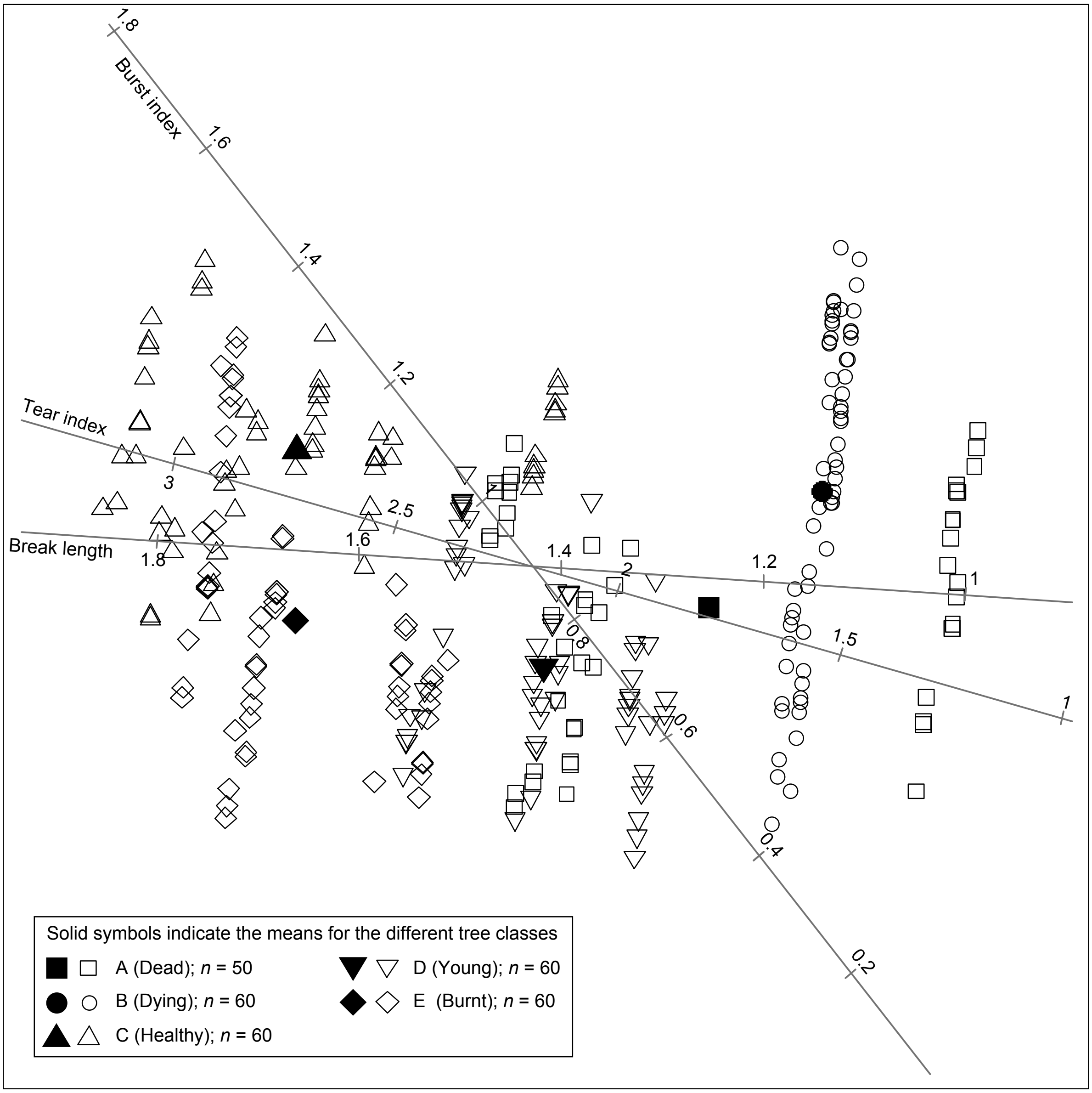

Figure 8: Canonical variate analysis biplot that optimally separates the means of the five tree classes with respect to the variables burst index, tear index and breaking length. All individual samples are also interpolated into the biplot to give a graphical display of the overlap/separation between the five tree classes. The calibrated biplot axes representing the variables are utilised similar to the axes of an ordinary scatterplot by projecting any point in the graph perpendicular onto an axis to read off its value for that particular variable. In particular, notice that all the class means for all three variables can be determined graphically almost without error in this way

Strength properties

When considering Figures 5 and 6 it is noted that the Healthy tree class (C) and Burnt tree class (E) have significantly higher strength properties than the other three tree classes (Young, Dying and Dead). Essentially, the Healthy and Burnt classes are similar because the Burnt trees were affected only on the outside; beneath the bark the fibres were not damaged and remained largely unaffected.

Generally, the pulp from the tree classes developed increased strength when subjected to increasing beating times. With the tear index, both the Healthy and Burnt tree classes ended, like for the burst index, with the higher values. The strength properties for these classes were higher than the Young and Dead tree classes, while the Dying tree class did not respond to the increased beating times.

The breaking length of pulp, did not respond to the increased beating over time, although healthy and burnt fibres tended to have a longer breaking length.

Canonical variance analysis biplot

Scatter plots and box plots, as shown in Figure 8, are simple graphical devices almost universally understood and used in data analysis (Chambers et al. 1983). However, in an ordinary scatter plot, only two variables (characteristics measured for each data point) can be visually displayed at a time. The biplot, introduced by Gabriel (1971), provides a means for displaying, in a single graph, more than two variables (in this study three paper strength properties). Figure 8 shows a biplot, a specific two-dimensional scatter plot, showing all the sample points together on an axis for each of the three paper strength properties determined. These axes are calibrated in the original units of measurement allowing the reading-off of values by drawing a line perpendicular to the axis of the interested property and then merely reading off the value.

By studying Figure 8, conclusions with regards to the differences among the tree classes in terms of their respective strength properties can be drawn. For breaking length, it is evident that no strength development takes place due to increasing beating times. The tear index showed development over time, but it was not as prominent as the development of the burst index.

Conclusion

Although the prevalence of *S. noctilio* in *Pinus* plantations did not pose a risk with regards to the chemistry of pulpwood, it will have negative impacts on the process parameters and the quality of paper manufactured from these affected trees.

In this exploratory investigation, it is shown that dehydrated fibres from dead trees had significantly higher energy requirements during thermomechanical pulping than wood obtained from dying, healthy and young trees due to a lack of plasticity of the fibres. High pulp yield (87.5%) was recorded for pulpwood from the Dead tree class (class A); however, the pulp quality, measured as burst and tear indices and breaking length, was poor (Figures 5, 6 and 7).

Moreover, the thermomechanical pulp produced from dead, dying and young trees has consistently lower strength properties than that produced from a normal, healthy pulpwood source. Noteworthy is that all tree classes developed improved strength in most properties investigated when beaten for an extended period of time. Despite the poor initial values of young, dead and dying tree classes for burst and tear indices, as expected, some development of these properties were achieved.

In the younger trees, the most likely reasons for the reduced pulp quality are that fibres are from the relatively large portion of juvenile wood and are usually shorter than mature wood fibres. Fibres from dead and dying trees were dehydrated and had very little elasticity, thus were not pliable and consequently did not process easily. The wood from dying trees had higher resin (pitch) levels and the hydrophobic extractives may have resulted in lower bonding ability (du Plessis et al. 2008). In all the strength tests conducted, Healthy trees (class C) had the highest values after the 5 min beating period, they are thus the optimum fibre for the various classes considered.

Based on the chemical properties of the wood (du Plessis et al. 2008) and paper strength properties, the following is suggested. *Pinus patula* trees infected by *S. noctilio* should be allowed to reach rotation end, currently around 12–14 years, at which time all the infected trees should be harvested and pulped. Utilisation of pulpwood at various stages of wood deterioration due to *S. noctilio* infestation and fire damage to the tree will not cause extractives levels to rise above unacceptable process levels if normal healthy wood is mixed with a constant but relatively small portion of the affected wood. Caution should, however, be exercised if a relatively large portion of wood from dead trees (dead for more than two years and as a result with dry fibres) is acquired and processed for pulp. This will cause a distorted processing environment characterised by relatively high energy consumption. The resultant paper quality will display lower burst and tear indices. Large amounts of pulp from such tree class, which necessitates additional refining time and energy to improve quality, should be largely avoided for papermaking.

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