The most important eucalypt fiber properties for fiber network strength and structural property development

Iiro Pulkkinen: Post-Doc. Researcher, Aalto University, Finland, iiro.pulkkinen@aalto.fi
Susanna Kuitunen : Ph.D Candidate, Aalto University, Finland,susanna.kuitunen@aalto.fi
Ville Alopaeus : Professor, Aalto University, Finland, ville.alopaeus@tkk.fi

Abstract

The objective of this study was to examine inter-fiber bonding and fiber segment activation as basic phenomena: how different raw material parameters and fiber property distributions affect bonding and activation, and in turn, how bonding and activation relate to end use properties of paper, especially to strength and structural properties. The most common fiber property distributions measured with fiber analyzer were used to predict paper technical properties, and based on these results evaluate the relative effects of bonding and fiber network activation. A fiber network activation model developed earlier by Pulkkinen et al. (2010)[1] was used to characterize how changes in fiber shape and dimensions affect paper strength.

A fiber swelling model was then combined with the network activation model to account for water inside fiber cell wall. The developed models can be used to predict paper strength and bulk not only from the fiber dimensions, but also through the computation of FSP from the amount of fiber bound acids and chemical composition of the fiber suspension.

Keywords: fiber network activation; property distributions; bonding; swelling; modeling; tensile strength.

Introduction

Nowadays the paper machines are running record speeds, up to 2000 m/min. At the same time, paper makers want their paper to have high bulk and still meet the wet-end strength requirements set by the increased paper machine speed. This is possible only if the process is optimized. Higher bulk results in easier water removal, and good bonding ability and high network activation results in higher tensile strengths [1-2]. Fiber quality plays an important role in these matters. Improved drainability means higher throughput, and consequently high profitability. The possibility of using high throughput techniques in fiber analyses, such as automated fiber analyzers, enables the prediction of paper technical properties of clone samples that can easily amount up to thousands individuals. A well established quality predicting parameter including information about fiber dimensions and their swelling ability, both of which are easily measurable means high savings in laboratory costs.

Because of this delicate relationship, it is crucial to understand the interactions between pulp fibers and the role of different factors that may have an influence on paper properties. With hardwood fibers in general, fiber length can be considered very homogeneous fiber property. Thus the effect of fiber length can be considered small in comparison to other properties, such as fiber cross sectional properties, in determining the structural and strength properties of paper. More emphasis should be placed on studying the transverse dimension distributions of the fibers and the structure of fiber wall as their importance on hand sheet properties of both softwoods and hardwoods have been suggested in several studies [2-4]. Also the geometrical shape of the fiber (fiber curl) has to be considered as it is an important factor for fiber network activation [5]. Fiber wall thickness distribution has been found to influence the packing of eucalypt fibers to a great extent, making fiber wall thickness the most important parameter for bulk density [6].

The strength of pulps consists of at least three components; single fiber strength, fiber-fiber bond strength per unit area and the total fiber-fiber bonded area [7]. In addition to proper choice of wood raw material, surface modification with carboxymethyl cellulose produces fibers with greater bonding potential and therefore considerably higher tensile strength [8-9]. This is partly due to higher swelling and more straightened fibers and hence higher fiber network activation [9]. Hence, fiber swelling is an important property in paper making. It has been noted that the fiber swelling depends on the amount of fiber bound acids and also on the ionic strength, type of the electrolyte and pH of the suspension.

In this study, the fiber network activation model using fiber dimension parameters and swelling property data developed by [1,10] was used to simulate tensile strength properties of eucalypt fiber network.

Materials and Methods

The samples for this study were collected from Western Uruguay. They presented 40 E. *grandis* families of 6 stems each collected from breast height (approx. 1.3 m). The maceration of the samples was done according to Wardrop and Dadswell (1947) [11].

The pilot trials were conducted at VTT. The chip samples were cooked in 15 liter electrically heated rotating autoclaves to a target kappa number of 18 ± 1 using the kraft process. Sample size was 4 kg o.d. chips. After the cooks the pulps were washed with deionized water, screened on a flat screen (slots 0.3 mm and 1.0 mm) dewatered on a suction filter and homogenized for 2 minutes. Selected unbleached pulps were bleached with the DEDED sequence to a target brightness of 90 +%. Hand sheets were made according to the standard ISO 5269-1. The laboratory sheets were dried under restraint. The drying included sheet making (90 g/m^2) in a dynamic sheet former, drying of the sheets in a ventilated oven (90 ˚C) attached to a frame. The targeted dry matter content after drying was 90%.

The pulps were soaked in water (> 4h) before refining. $MgSO_4$ was used to raise the conductivity of the pulp slurry to a level of approximately 90 mS/m. The refining trials were made in a Voith LR 1 laboratory refiner as follows:

Fillings	disk 2/3-1.46-40D
Consistency	4%
Specific edge load	0.4 J/m
SRE, kWh/t	0, 40, 80 and 120
Temperature	23 °C

After refining, hand sheets were made according to the standard ISO 5269-1. The laboratory sheets were dried under restraint. The drying was performed in a climate control room (23 °C and relative humidity (RH) of 50%). After drying, the handsheets were tested according to the following standards and methods:

- apparent density EN ISO 534
- tensile properties EN ISO 1924-2
- Internal bonding strength (Scott Bond) Tappi T569:00
- water retention value (WRV) SCAN-C62:00

Carbohydrate composition of the pulp samples was determined using a method; utilizing sulphuric acid hydrolyzes at 120°C to degrade the carbohydrates into monosugars, based on Tappi standard T222-om0. Monosugars were then analysed by ion chromatography (Metrohm 817 Bioscan system).

Optical image analysis- what is actually measured?

Fiber analyzer technological advances are nowadays really fast, and analyzer's ability to characterize the fibers and process measured information is increasing at a rapid pace. There are several alternatives to choose from. Several studies have been

conducted comparing fiber length and coarseness measurements of different off-line analyzers [12-13]. The FiberLab® analyser and other Kajaani fiber analysers (such as Kajaani FS-100 and 200) have frequently been compared to other analyzers or analysis methods in terms of pulp fiber dimensions and calculated values [13-15] or in terms of comparing wood fiber dimensions to pulp fiber dimensions [15] The magnitude of analyzer results between analyzers being different they nevertheless showed good linearity [12-13, 15]. The biggest problems associated with the automated fiber analyzers are that fiber collapsibility is difficult to observe, cellulose crystallinity may affect the sharpness of projected image and detection of fiber walls [16-19]. This, among other things, hinders the more routine use of fiber analyzers in on-line analysis at different parts of the pulp/paper mill.

Fiber wall thickness

Recent study has shown that there exists a correlation between fiber wall thickness of eucalypt pulp fibers and cellulose crystallinity [18]. This may have an effect on the measured fiber wall thickness values [16] Fiber coarseness and also fiber wall thickness correlate reasonably well with tensile- and tear strength [3, 6]. The structural properties (for example bulk density) are also generally correlated with fiber wall thickness [3, 20].

Fiber curl

During the pulping process, the fibers are exposed to stresses and become compressed, twisted and curled. These deformations can also arise during the thickening of the pulp. Curls are smooth bends of the fibers while kinks change the direction abruptly and form an angle. Curl is commonly measured with the curl index, *CI* given by the equation (1)

$$CI = \left(\frac{l_c}{l_p} - 1 \right) * 100\% \qquad (1)$$

where l_p is the projected length of a fibre, and l_c is the contour length (Figure 1).

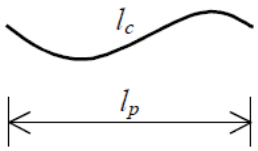

Figure 1. A curled fiber with projected length, l_p and contour length, l_c.

The mechanisms of curl induction, removal and retention in pulp fibres have been discussed by many scientists [21-23]. Curl, in contrast to curvature, is a size invariant descriptor.

Simulation model for fiber network strength

The activation coefficient presented earlier in Pulkkinen et al. (2010), (2011)[1, 10] is as follows:

$$A(n) = \frac{\sum_{i=1}^{n}\left(\left(\frac{fwt}{l}\right)_i^{(1/WRV)}\right)}{n} \times \frac{\sum_{i=1}^{n}\left(CI_i^{(1/WRV_i)}\right)}{n} \quad (2)$$

where fwt is fiber wall thickness, l is length-weighted fiber length, n is the total number of fibers and I is fiber index. Smaller A(n) means better activation potential.

In activation of fiber network

(i) Increasing fiber length improves the activation by introducing more contacts for an individual fiber with other fibers, therefore increasing their ability to transmit forces. As this may not be relevant for eucalypt fibers, it can have bigger influence when softwood fibers are concerned.

(ii) A decrease in fiber wall thickness improves fiber network activation by increasing the bonded area of fibers in fiber crossings. Also, thin walled fibers are more conformable, hence fibers become more entangled to each other.

(iii) Decreasing fiber curl improves fiber network activation by enhancing the delivery of in-plane strength throughout fiber network. The more straight a fiber is, the more effectively strength is delivered to adjacent fibers.

(iv) Water retention value increases with increasing fines content or by increasing fiber swelling by means of refining etc. Initial high values of WRV can be due to for example chemical composition of fibers or in the amount of primary fines.

Hence, the activation coefficient decreases and activation of fiber network increases when fiber length and WRV increases, or fiber wall thickness and fiber curl become smaller. The values of the activation parameter were used to describe the bonding and activation phenomena by correlating them with tensile properties with a clone test set. The length dependency of the activation coefficient was deduced from a set of softwood, hardwood and TMP pulp fibers [10]. The reduced strength potential of industrially refined fibers [24-25] can be characterized using the activation coefficients introduced. The effect of the change in fiber curl as a function of refining is therefore excluded, although fibers are presumably straightened as WRV increases.

Results

Fiber network activation model

Figure 2 shows the measured tensile index values for handsheets of Voith Sulzer refined fibers as a function of simulated fiber network activation coefficient based on fiber dimensions and fiber wall swelling capacity (WRV). As a reference, the Page model [26] that uses fiber dimensions, individual fiber strength data and bonding characteristics to calculate fiber network strength is presented. As Figure 2 depicts, both methods result in accurate solution at low specific refining energy (SRE) levels.

The reduced predictability of tensile index at high values of strength seen in the right part of Figure 2 emerges from PFI refining characteristics used to build the activation

model. Disk refining will expose fibers to a greater damage than PFI refining lowering tensile strength values observed for high refining levels. When more data is available for varying conditions, a more accurate description of fiber strength can be given. In this study a conversion factor of

$$E = \frac{0.15\,kWh}{metric\ tonne * revolution} \qquad (3)$$

was used. In fact, this is the form to be used in the case of bleached eucalypt kraft fibers (estimated effective energy of 0.54 J/g/rev) [27]. The refining intensity in the PFI mill has been estimated to be approximately 1 kJ/kg/impact [28]. Considering the specific edge load (SEL) normally used in industrial refiners for hardwoods (approx. 0.2-0.4 J/m), which would correspond 11-12 kJ/kg/impact, it is concluded that PFI mill is a very low intensity refiner. Nevertheless, as uncurled fibers have been found to improve tensile strength and load-transferring efficiency [1, 22-23], it is necessary to take into account that PFI refining will more likely produce straight fibers than low or medium consistency disk refining [29].

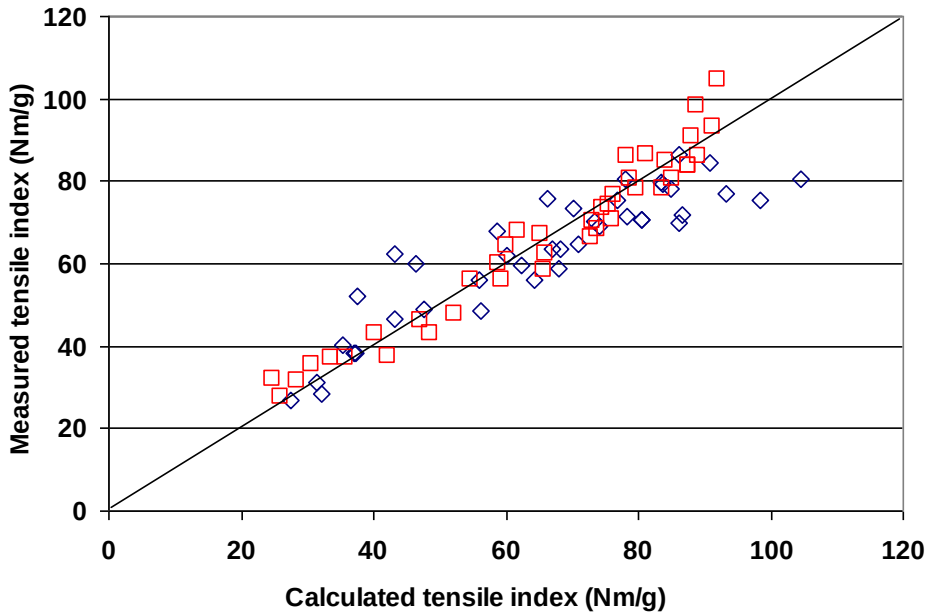

Figure 2. Measured tensile strength as a function of calculated tensile strength based on a) the activation model- diamonds and b) the modified Page model- squares.

Simulation model for fiber wall swelling

Fiber swelling is one important factor contributing to paper properties. A fiber swelling model created by Kuitunen et al. (2011) [30} can be used for predicting the effect of chemical composition of water and the amount of fiber bound acids (hexenuronic and methylglucuronic acids) on the WRV. The model for paper properties utilizing fiber dimensions and WRV data used in this paper can be used to study the effect of calculated WRV on paper technical properties. Previously, especially paper strength properties have shown to be dependent on fiber network activation [1, 31]. When fiber network bonding ability is sufficiently high fiber network activation increases together with increased fiber wall hydration level.

The results of fiber swelling model simulations are presented in Figure 3. As expected, fiber network strength increased together with increasing FSP value. The effect of fiber bound acids (ranging from 30-70 mmol/kg fibers on tensile index is notable.

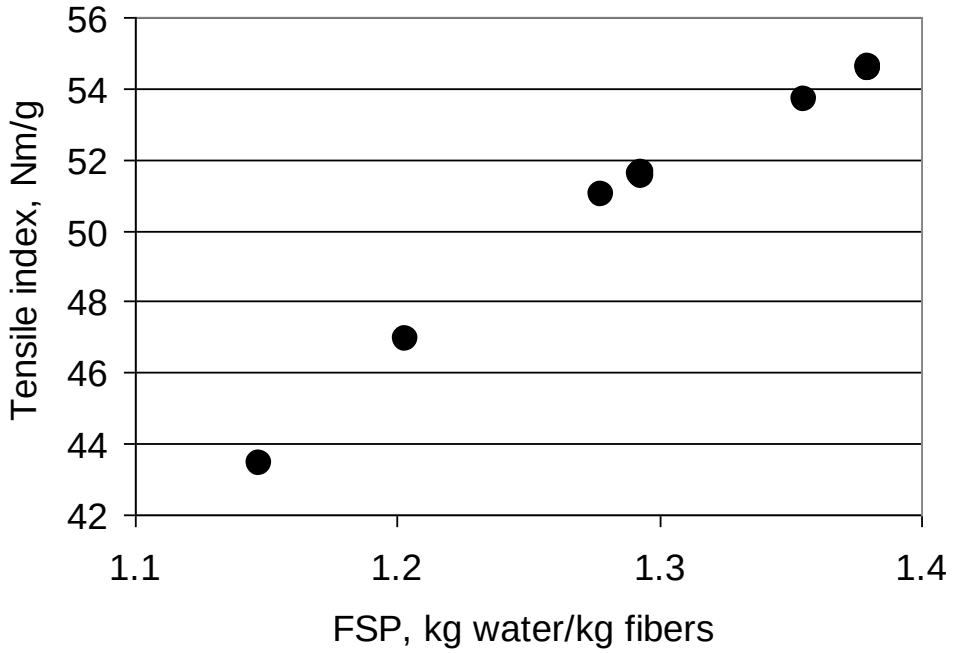

Figure 3. Effect of FSP on tensile index [30]. Fiber bound acids range from 30-70 mmol/kg fibers.

Practical considerations

The tree species and individual wood logs inside a given species determine the range of fiber structure, chemical composition and dimensions modified by the pulping, bleaching and refining process, and therefore the properties of the final paper product. The higher amount of fiber bound acids in paper could lead to higher strength of the paper as demonstrated above. With a constant strength target, less refining energy is required using a pulp in more swollen state. Higher bulk in paper is also achieved if fiber wall water absorbing capacity is increased. This would be especially valuable in tissue manufacturing. Paper mill profitability will therefore be increased due to the smaller demand of wood raw material.

Conclusions

Multidimensional fiber analyzers give new possibilities to combine traditional lab methods for predicting product quality. The most important thing is that they are comparable to some physical property that can be easily measured. From a practical and engineering point of view it is important that all parameters of a given model could be easily measured in the laboratory in order that the model could be widely applicable. Fiber curl and fiber wall thickness were found to be the most promising fiber parameters for use in the evaluation of eucalypt fiber quality potential in terms of fiber network strength. A parameter to describe fiber network activation and fiber-to-fiber bonding was developed based on fiber distributions. The difference in fiber wall swelling potential was taken into account by adding WRV as one of the variables. The effect of the amount of fiber bound acids, pH and ionic strength on the fiber swelling, and therefore on the bonding and activation potential of fibers can be studied in with a recently developed fiber swelling model based on Donnan equilibrium model and Hooke's law.

By using the fiber network activation model together with the fiber swelling model, the strength losses along the fiber line can be estimated based on easily measurable fiber based parameters.

References

1. Pulkkinen, I.; Fiskari, J.; Alopaeus, V., Holzforschung 64(2):201 (2010).
2. Mohlin, U.-B. and Salmén, L., Proceedings. In SPCI International Conference, Stockholm, Sweden, pp.1 (2005).
3. Paavilainen, L., Paperi ja Puu 75(5): 343 (1993).
4. Retulainen, E. Ph.D. Thesis, Helsinki University of Technology, Espoo, Finland (1997).
5. Mohlin, U-B. and Hornatowska, J., Appita J. 59(3):225 (2006).
6. Pulkkinen, I., Doctoral Thesis, Aalto University School of Science and Technology, Espoo, Finland, 74 (+ 87) pages (2010).
7. Johansson K., Thuvander F., Germgård U., Appita J. 54**(**3): 276 (2001).
8. Laine, J., Lindström, T., Nordmark, G., Risinger, G., Nordic Pulp and Paper Res. J. 15(5):520 (2000).
9. Duker, E. and Lindström, T., Nordic Pulp and Paper Res. J. 23(1): 57 (2008).
10. Pulkkinen, I.; Alopaeus, V., Holzforschung. *Accepted for publication* (2011).
11. Wardrop, AB. and Dadswell, HE., Australian Journal of Botany *3*(2): 177 (1947).
12. Hirn, U. and Bauer, W., Lenzinger Berichte. 86: 96 (2006).
13. Turunen, M., Le Ny, C., Tienvieri, T., Niinimäki, J., Appita J. 58(1):28 (2005).
14. Muneri, A. and Balodis, V., Appita J. 50(5): 405 (1997).
15. Richardson, J.D., Riddell, M.J.C., Burrell, P., Proceedings of 57th Appita Annual Conference and Exhibition, Melbourne, Australia, 5-7 May, 2003, pp.315 (2003).
16. Jordan, B.D. and O'Neill, M.A., The Journal of Pulp Paper Sci. 20(6): J172 (1994).
17. Xu, L., Filonenko, Y., Li, M., Parker, I., Appita J. 50(6): 501 (1997).
18. Pulkkinen, I., Fiskari, J., Alopaeus, V., J. of Applied Sciences 9(22):1 (2009).
19. Wan, Y., Yao, L.., Xu, B., Intelligent Computing and Intelligent systems, 20-22 Nov., Shanghai, China, pp.247 (2009).
20. Mörseburg, K., Hultholm, T., Lundin, T., Lönnberg, B., 5th PTS-Symposium, April 14-15, Dresden, Germany, pp.13/1 (1999).
21. Hartler, N. Nord. Pulp Paper Res. J 10(1): 4 (1995).
22. Page, D.H., Seth, R.S., Jordan, B.D., Barbe, M.C., Transactions of the 8th Fundamental Research Symposium held in Oxford September 1985, ed. V. Punton. Vol. 1, Mechanical Engineering Publications Limited, London, pp. 183 (1985).
23. Seth, R.S. Pulp and Paper Can. 107(1): 34 (2006).
24. McLeod, J.M., Cyr, M., Embley, D., Savage, P., Journal of Pulp Paper Sci. 13(3):J87 (1987).
25. McLeod, J.M., International Pulp Bleaching Conference, June 14-16, Stockholm, Sweden, pp. 31 (2005).
26. Page, D.H.. Tappi J. 52(4):674 (1969).
27. McKenzie, A.W., Prosser, N.A., Appita 34(4):293 (1981).
28. Kerekes, R.J., Tappi J. 4(3):9 (1990).
29. Wang, X., Ph.D. Thesis, Helsinki University of Technology, Espoo, Finland (2006).
30. Kuitunen, S., Pulkkinen, I., Tarvo, V., Alopaeus, V., In Proceedings: The 5th ICEP, Porto Seguro, Bahia, Brasil, *In Press* (2011).
31. Jentzen, C.A., Tappi 47(7):412 (1964).