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Citation for the peer-reviewed published paper:

Forsström J, Torgnysdotter A, Wågberg L. Influence of fibre/fibre joint strength and fibre flexibility on the strength of papers from unbleached kraft fibres. Nordic Pulp & Paper Research Journal. 2005;20(2):186-191.

URL to article at publishers site:

<http://dx.doi.org/10.3183/NPPRJ-2005-20-02-p186-191>

Influence of fibre/fibre joint strength and fibre flexibility on the strength of papers from unbleached kraft fibres

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KEYWORDS: Bonded area, Bonding strength, Counter-ions, Flexibility, Hornification, Joints, Pulp yield, Tensile strength, Unbleached pulp

SUMMARY: The joint strength between single fibres and its influence on strength properties of papers was evaluated, taking into account the effect of pulp yield, ionic form of the carboxyl groups and drying. Fibre/fibre joint strength stayed almost constant for pulps with yield between 45 % and 50 %. Further increasing the pulp yield increased the joint strength until a maximum value was reached at a pulp yield of around 57 %, after which the joint strength decreased. Joint strength correlated well to paper tensile strength for never dried fibres, i.e. a lower joint strength resulted in lower sheet tensile index. The decrease in sheet tensile index was not as pronounced as the decrease in joint strength. Changing counter-ion from Na^+ to Ca^{2+} or H^+ did not affect fibre flexibility, although it reduced the joint strength as the molecular contact area decreased due to a reduced swelling upon changing the counter-ions. Drying the high yield pulp lowered both the joint strength and the sheet tensile index to the same extent. The sheet tensile index, for the low yield pulp, decreased much more than the fibre/fibre joint strength after drying the fibres. In conclusion, a combination of a lower fibre flexibility, resulting in fewer contact points between fibres in the sheet, and a lower joint strength after drying was responsible for the reduction in sheet tensile index.

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The characteristics of single fibres will naturally affect the dry strength, density and E-modulus of a formed paper network. Fibre characteristics are affected both by mechanical treatments, e.g. beating and drying, and chemical treatments, e.g. pulping and bleaching. It has long been debated whether the single fibre strength or the fibre/fibre joint strength is most important for paper strength (Davison 1972). As the load-bearing component of the fibres is the cellulose micro fibrils (Fellers 1986), a network where the fibres are utilised in the best way may hence show an increase in strength with decreasing pulp yield. However, the fibre/fibre joint strength also significantly affects paper strength (Torgnysdotter, Wågberg 2003; Torgnysdotter, Wågberg 2004). The fibre/fibre joint strength is highly affected by the macroscopic softness, i.e. the transverse modulus, of the fibre (Stone and Scallan 1965a) and the wet flexibility of the fibre surface. A soft fibre wall, i.e. a fibre wall with low transverse modulus, allows for a larger molecular contact area between the fibres and a better mixing of fibrils on

the surface during drying and consolidation, resulting in a higher joint strength.

Flexibility correlates well with pulp yield, sheet density and sheet strength, (Forgacs et al. 1958, Tam Doo et al. 1982, Mohlin 1975, Steadman and Luner 1985, Page 1985) and depends on fibre morphology, fibre chemistry and the unit process that the fibre has been subjected to. Wet fibre flexibility also controls the number of joints formed in the sheet (Clark 1985; Wahlström 1988; Torgnysdotter, Wågberg 2004). The number of joints formed in the fibre network naturally influences the network properties (Askling et al. 1998) and, thus, the number of possible joints is a third property to take into consideration when evaluating sheet properties.

The fibre/fibre joint strength is usually evaluated by application of Page's equation (Page 1969) where the so-called relative bonded area (RBA) is estimated by light scattering of papers made from the same type of fibres and pressed to different densities. As this method only gives an estimation of the fibre/fibre joint strength, more direct measurement of the joint strength is sometime needed. This is a challenging and difficult task and very few studies exist that measures the strength in a fibre/fibre joint. Davison (1972) measured the fibre/fibre joint strength by pulling single fibres out from a paper. Stratton and Colson (1990) and Torgnysdotter and Wågberg (2003) measured the joint strength directly in a perpendicular cross between two single fibres and correlated the joint strength to the strength of the formed paper.

The previous statements regarding paper and fibre properties change if the fibres are dried (Chatterjee, Dodson 1994, Stone, Scallan 1965b, Laivins, Scallan 1993). Drying alters the mechanical properties of both the fibre and the paper as drying and rewetting of fibres induces crosslinking between the micro fibrils due to additional hydrogen bonds (Laivins, Scallan 1993). Sheets made from hornified fibres are less dense and have lower tensile strength than sheets prepared from virgin fibres (Chatterjee et al. 1992; Howard, Bichard 1991). Drying collapses the outermost fibre surface, creating a stiffer fibre surface, which in turn decreases the molecular contact area in the contact zone and hence weakens the fibre/fibre joints (Page 1969; Stratton, Colson 1990; Torgnysdotter, Wågberg 2003, Scallan and Tigerström 1992). The fibre and paper properties response to drying naturally also depends on the virgin fibre material, the drying process, utilisation of fibres during re-pulping, etc.

Today's increased use of recycled fibres creates a unique situation where fibres that have been dried and rewetted several times are introduced into the paper machine. These recycled fibres exhibit properties that

differ from virgin fibres, and several critical paper properties are negatively affected by the drying and rewetting cycle. In order to optimise the fibre treatment to best utilise the inherent properties of a certain raw material, it is important to study in detail the different fibre properties, the effect of different treatments, and the correlation between fibre and paper properties. This type of study is best conducted using a well-characterised fibre material to give a better understanding and a clearer view of how different fibre and paper properties are correlated. The influence of pore structure on paper strength was shown in a previous work (Forsström et al. 2004). The present paper is a continuation of that work in which the influence of fibre/fibre joint strength and fibre flexibility on paper strength was investigated. Together with earlier work on how different treatments influence pore structure (Andreasson et al. 2003; Andreasson et al. 2004; Forsström et al. 2004) and paper strength via chemical additions (Andreasson et al. 2004; Gärdlund et al. 2003), the present work adds another key component to explaining the relation between fibre surface properties, properties of the internal structure of the fibres, fibre flexibility, fibre joint formation, properties of the fibre/fibre joint and paper strength.

Experimental Section

Materials

Cooking

A total of six different spruce pulps were laboratory cooked according to a conventional kraft process in an 18-liter digester. Pulps with target kappa numbers of 110, 85 and 60 were prepared by treating wood chips with 185-kg effective alkali, EA, per tonne dry weight. The liquor-to-wood ratio was 3.2: 1. The upper cooking temperature (160°C) was reached after 100 minutes and the sulfidity was 31 %. After cooking, the pulps were washed and very mildly refined to disintegrate the treated wood chips. Finally, the pulps were dewatered to a dry content of about 25 %. Pulps with target kappa numbers of 35, 25 and 16 were prepared by treating wood chips with 200-kg EA, per tonne dry weight, at a liquor-to-wood ratio of 3.5: 1. The respective cooking temperatures were 156°C, 161°C and 166°C with a sulfidity of 35 %. The pulps were washed after cooking, defibrated using a propeller defibrator and screened in a Wennberg screen (0.15 - mm slots). Subsequent fractionation in a Britt Dynamic Drainage Jar (BDDJ) equipped with a 125 P screen removed the fine fraction.

Pulp Treatment

The long fibre fraction was diluted to 2 % fibre concentration and the pH of the suspension was adjusted to 2 with HCl and maintained for 30 minutes. The pulp was then washed several times with deionised water until the pH reached 4.5, corresponding to the H⁺ form of the carboxyl groups in the fibres. The carboxyl groups could then also be converted to their Na⁺ form and Ca²⁺ form. For the Na⁺ form, the pulp was treated with NaOH and

0.01 M NaHCO₃ at pH 9 for 30 minutes, after which it was washed with deionised water down to pH 8. The pulp could then be converted to its Ca²⁺ form by treating the Na⁺ form pulp with NaOH and 0.01 M CaCl₂ at pH 9 for 30 minutes and then washing the pulp to pH 8 with deionised water. These pulps were not allowed to dry before testing and were stored at 4°C with a solid content of ~ 20 % until further use. The pH and counter-ions of the different pulps were varied using NaOH, NaHCO₃, CaCl₂ and HCl of analytical grade.

Methods

Sheet preparation and testing

Sheets with a grammage of 120 g/m² were prepared from different pulps according to EN-ISO standard 5269-2. Na⁺ and Ca²⁺ pulp suspensions were prepared at pH 8, whereas the H⁺ pulp suspension was prepared at pH 4.5. The papers were tested with respect to dry tensile strength properties according to SCAN standard methods (SCAN-P:67) where the variation coefficients varied between 3 to 6 %. Only unbeaten, fines-free fibres were used for the sheet preparation in order to determine the effect of the structure in the fibre wall due to component removal following the cooking procedure.

Fibre crosses

The fibre crosses were prepared according the method initially outlined by Stratton and Colson (1990), except that the fibres were not dyed (Torgnysdotter, Wågberg 2003). The chemical conditions were the same as during paper formation. The technique for fibre cross preparation were made more effective by preparing a very dilute fibre suspension from which a small volume was added to a teflon-faced silicon disc with 8 mm in diameter. The fibres were allowed to sink to form a thin fibre web with only a few fibres. A second teflon disc was placed face down on top of the fibres. The fibre web were put under a nominal compressive load of 0.12 MPa and allowed to dry at 105 °C for 2 hours. From the dry fibre web perpendicular fibre crosses were chosen and picked out, the fibre crosses were stored at 50 % RH and 23°C until testing. A tensile testing stage was designed at Mid Sweden University for fibre strength and fibre cross testing. One of the stage jaws was held stationary while the other was displaced during testing at 2 µm/s. A load cell from Sensotec® with a working range of 0 – 150 grams was used. The sample was fixed to the table of the load bench with Loctite 401® glue. Approximately 30 – 60 fibre crosses were tested for each measuring point and variation coefficients of the fibre joints were 45-70 %.

Fibre flexibility

Fibre flexibility was measured at STFI on a STFI Fiber Master where the form factor of the fibres was measured at two different flow rates (Fransson et al. 1992). The form factor is defined as the ratio between the fibres extension in space and length and is presented in percentage, where 100 % represents a completely straight

fibre. Fibre flexibility is then given as the difference between the form factor at high and low flow rates. All measurements were repeated twice and variation coefficients between 1 and 3 % were obtained. The pH values were kept the same as for the sheet making procedure. The wet fibre flexibility and kink related properties were measured, as well as the fibre length, width and shape factor.

Surface charge

Polyelectrolyte adsorption determined the surface charge of the pulps according to the method described by (Wågberg et al. 1989). In this method, available charges on the external surface of the fibre are estimated by the adsorption of a high molecular mass ($1.2 \cdot 10^6$) poly-DiallylDiMethylAmmoniumChloride (pDADMAC). All experiments were repeated three times and variation coefficients between 1 and 3 % were obtained.

Drying procedure

Pulps were dried freely at room temperature to a solids content of ~96 %, after which the pulps were rewetted in deionised water. After rewetting, the pulps were treated with NaOH and 0.01 M NaHCO_3 at pH 9 for 30 minutes before being washed with deionised water down to pH 8. This was done to ensure that the pulps were in their Na^+ form.

Results

Fibre properties

Fibre flexibility is believed to affect sheet density and the ability to form fibre/fibre joints in papers from these fibres. Generally, it is believed that more flexible fibres lead to a higher sheet density and a higher amount of fibre/fibre joints (Forgacs et al. 1958). As can be seen in Fig 1, wet fibre flexibility increased as pulp yield decreased and the increase was larger for pulps with higher yield. It can also be seen that electrostatics, i.e. changes in counter-ion, did not affect wet fibre flexibility. Dried and rewetted fibres with low pulp yield had low flexibility, whereas fibres with pulp yield higher than approximately 52 % were not affected at all by drying.

The fibre/fibre joint strength is plotted in Fig 2 against pulp yield, showing that the never dried fibres and once dried fibres both experienced a maximum in joint strength at a pulp yield of approximately 57 %, the maximum being more pronounced for the never dried fibres. The joint strength for pulps with yield lower than approximately 49 % did not decrease significantly after drying. The dried fibres exhibited overall lower joint strengths than never dried fibres. The joint strength further diminished with repeated drying and rewetting, although the decrease was not as pronounced after the first drying and rewetting cycle. In Fig 2, it can also be seen that the joint strength was significantly lowered when replacing Na^+ as counter-ion with Ca^{2+} or H^+ .

Surface charge is plotted against pulp yield in Fig 3. A rise in surface charge occurred with pulp yield,

Fig 1. Fibre flexibility as a function of pulp yield and counter-ion for unbleached kraft pulp. The effect of drying is also shown for the Na^+ form. The lines are merely a guideline for the eye.

Fig 2. Fibre-fibre joint strength as a function of pulp yield for unbleached kraft pulp. The effect of changes in counter-ion is shown for pulp with yield 56.6 %.

Fig 3. Fibre surface charge as a function of pulp yield for pulp in its Na^+ form.

reaching a maximum at around 57 %. Pulps with higher yield exhibited lower surface charge. Drying and rewetting slightly diminished the surface charge, and the relative percent decrease was highest for the low yield pulp.

Sheet properties

The tensile strength index is plotted in Fig 4 versus pulp yield for sheets made from never dried pulps and dried pulps. The carboxyl groups of the never dried fibres were converted to different ionic forms allowing for the importance of electrostatic interactions, inside the fibre wall and also between the fibres, for the obtained paper properties to be investigated. For never dried fibres with carboxyl groups in their Na^+ form, tensile strength increased slightly as the yield was decreased, eventually decreasing significantly below a critical yield. Changing the carboxyl groups from Na^+ form to either Ca^{2+} or H^+ form lowered the tensile index, and changes in tensile

Fig 4. Sheet tensile strength index as a function of pulp yield and counter-ion for unbleached kraft pulp.

Fig 5. Sheet density as a function of pulp yield and counter-ion.

Fig 6. Fibre-fibre joint strength versus fibre surface charge for unbleached, never dried and once dried and rewetted kraft pulp in Na⁺ form.

Fig 7. Fibre-fibre joint strength versus sheet tensile index for unbleached kraft pulp with different counter-ion and different degrees of hornification.

strength due to differences in pulp yield were smaller. After subjecting the fibres to drying and rewetting, there was a continuous reduction in tensile index for the once dried fibres with decreasing pulp yield. It can also be seen that the tensile index continued to decrease upon drying and rewetting several times, although the decrease

was not as great as after the first drying and rewetting cycle.

In Fig 5, the sheet density is shown as a function of pulp yield, ionic form of carboxyl groups on the fibres and drying. All sheets made from never dried pulps became denser with decreasing yield, and sheets in their Ca²⁺ form were most dense. Upon drying and rewetting, the sheet density was almost unaffected for high yield pulps, whereas a dramatic decrease for pulps with lower yield was exhibited. Drying and rewetting the fibres several times decreased the density even further.

Discussion

Correlation between fibre and sheet properties

The sheet density is usually taken as a measure of how well the fibres conformed towards each other during sheet consolidation. As can be seen when comparing Figs 4 and 5, a simple correlation does not exist between tensile strength and density for the papers in this investigation. It might be concluded that the density cannot be used to clarify the mechanisms responsible for the creation of paper strength. It has previously been shown that the size of the pores inside the fibre wall affects paper strength (Forsström et al. 2004). Larger pores create a more conformable fibre wall, thus the molecular contact area between fibres increases, resulting in a higher fibre/fibre joint strength. This large dependence of the fibre/fibre joint strength on molecular contact area between the fibres has also been recently demonstrated (Torgnysdotter and Wågberg 2003) for regenerated cellulose fibres where the surface charge was modified by carboxymethylation. The same study also found that the fibre/fibre joint strength strongly correlates with sheet strength of paper made from the same type of fibres. It was therefore of interest to investigate whether a correlation between fibre/fibre joint strength, surface charge and sheet tensile index could also be found for the kraft pulps used in the present study. These results from this comparison are shown in Figs 6 and 7.

Fig 6 shows that a small decrease in surface charge for the never dried high yield pulps greatly diminishes fibre/fibre joint strength, whereas the fibre/fibre joint strength was virtually unaffected by changes in surface charge for never-dried, low yield pulps. It can be seen in Figs 2 and 6 that the joint strength decreased upon drying the fibres, and that the decrease was more pronounced for the high yield pulp. It has previously been shown that pulps with higher surface charge have stronger joints, such that fibre surface softness is of primary importance for the utilisation of joint strength (Torgnysdotter 2003). Though it is obvious from Figs 2 and 6, when comparing fibres where the fibre properties have been drastically altered, i.e. by pulping or drying, a simple relationship between joint strength and surface charge is not found. Drying lowers the joint strength much more for the high yield pulps than for the low yield pulps, though a reduction in surface charge was approximately the same

irrespective of pulp yield. Furthermore, it has been suggested (Andreasson et al. 2003) that the surface charge could be taken as a measure of the openness and ability of the fibres to form strong joints. Obviously, this holds only true for never dried fibres. The availability of the charge to a high molecular mass poly-DADMAC is almost the same for dried fibres, as seen in Fig. 2. The state of the fibre surface swelling, as displayed by WRV, is very different for the dried fibres, indicating that the conformability of the surface of the fibres is determined on a level below what can be detected by surface charge measurements. It can also be concluded that the charges on the surface of these fibres are not sufficient to create swelling forces that can overcome the binding forces created during drying of the fibres.

A more sophisticated explanation than a linear relationship between tensile strength and joint strength is needed. Torgnysdotter and Wågberg (2004) concluded that the paper strength, dominated by an adhesive fibre/fibre joint, is determined by the joint strength between the fibres and the number of active fibre/fibre joints per unit volume of the sheet. It was also concluded that higher fibre flexibility leads to a larger number of possible fibre/fibre contacts in the paper. However, it was found that the formation of efficient fibre/fibre contacts was not only affected by the flexibility of the fibres, but also by the molecular interaction between the fibres during formation of a fibre/fibre contact. In Fig 1, it can be noted that the pulps with lowest yield showed the largest flexibility, such that it is safe to conclude that the low yield pulps will have a higher number of fibre/fibre contacts, which should also lead to a higher sheet density. This was in fact found for these pulps, as shown in Fig 5. It can therefore be suggested that fibres with the largest flexibility allowed for a more efficient packing of the fibres and a higher sheet density, but the corresponding decrease in joint strength for these fibres actually decreased the paper strength for low yield pulps.

Pulps with different yields behaved differently upon drying, as shown in Figs 2 and 7. The large reduction in tensile index of the papers from pulps with high yield was accompanied with an almost equally large decrease in joint strength between the fibres. The decrease in joint strength can explain most of the reduction in tensile strength of the sheets. For the low yield pulps, however, the large reduction in tensile index cannot only be caused by weaker joints (compare Figs 2 and 7). Figs 4 and 5, show that the fibre flexibility and sheet density were lowered for the low yield pulps upon drying. This supports the earlier hypothesis that a combination of fibre flexibility and fibre joint strength controls the sheet strength for the fibres investigated in the present work.

Fig 7 shows that a change of counter-ion from Na^+ to Ca^{2+} or H^+ lowered the joint strength by more than 50 %, whereas there was only a 15-20 % decrease in the tensile index of the sheets. This large decrease in joint strength can be ascribed to a loss in surface swelling of the fibres when changing counter-ion to Ca^{2+} or H^+ , as the degree of dissociation of the carboxyl groups on the fibres decreases. The relatively smaller decrease in tensile index of the

sheets from these fibres is suggested to be due to a change in the electrostatic interaction between the fibres, as hypothesized in a recent work (Torgnysdotter and Wågberg 2004). There will be less available charges per unit area of the wet fibres as the carboxyl groups are changed to Ca^{2+} or H^+ . Since the flexibility of the fibres is only moderately influenced by changing to Ca^{2+} form, it is suggested, along with other recently published results (Torgnysdotter and Wågberg 2004), that more efficient fibre/fibre contacts are formed due to a decreased electrostatic interaction between the fibres during forming of the sheets. These results also support the hypothesis that the number of efficient joints per sheet volume and the joint strength between the fibres controls the sheet strength.

Conclusions

Fibre/fibre joint strength correlates to sheet tensile strength for unbleached kraft pulps, and it was shown that both fibre/fibre joint strength and sheet tensile index decreased with decreasing pulp yield. The decrease in fibre/fibre joint strength for never dried pulps was more pronounced than the decrease in tensile index of sheets made from these fibres. Changing counter-ion from Na^+ to Ca^{2+} or H^+ drastically reduced the joint strength, whereas the sheet tensile strength was only affected to a minor extent. It was suggested that a smaller electrostatic interaction exists between the fibres upon changing counter-ion from Na^+ to Ca^{2+} or H^+ , causing a smaller contact area and hence a weaker fibre/fibre joint. At the same time, this reduced electrostatic interaction allowed for more efficient fibre/fibre contacts, giving denser sheets with higher sheet tensile index. It was also shown that fibres with different yield behaved differently upon drying. The decrease in sheet tensile index for pulps with higher yield was caused by an equal decrease in joint strength. For the low yield pulps, a weaker joint strength could not explain the large decrease in sheet tensile index. Fibre flexibility, fibre/fibre joint strength and the number of efficient fibre/fibre contacts controls the sheet strength. The results shown in the present investigation support the hypothesis that the number of efficient joints per sheet volume and the joint strength between the fibres controls the sheet strength, previously suggested by Torgnysdotter and Wågberg (2004). In order to test this hypothesis even further, it is necessary to directly measure the interaction between model cellulose surfaces with carboxyl groups in different ionic forms and to measure the state of swelling of these contacts. These types of measurements (Fält 2002; Notley 2004) are currently being investigated in the laboratory of the authors

Acknowledgements

Co-workers at FSCN and KTH are appreciated for fruitful discussions. The authors acknowledge Andrew Horvath for linguistic revision of the manuscript. SCA AB and the Fibre Science and Communication Network (FSCN) at Mid-Sweden University are last, but not least, thanked for financial support.

Literature

- Andreasson, B., Forsström, J. and Wågberg, L.** 2003. The porous structure of pulp fibres with different yields and its influence on paper strength. *Cellulose* 10(2):111.
- Andreasson, B., Forsström, J. and Wågberg, L.** 2004. Crosslinking of the fibre wall by application of polycarboxylic acids, polymeric anhydrides and conventional wet strength resins and the influence of crosslinking on pore structure of the fibres. Accepted for publication in *Cellulose*.
- Askling, C., Wågberg, L. and Rigdahl, M.** 1998. Rheological characterization of dry-formed networks of rayon fibres. *J. Mat. Sci.* 33:1517.
- Chatterjee, A., Roy, D. N. and Whiting, P.** 1992. Effect of recycling on strength, optical and surface properties of handsheets. In "76th Annual meeting", CPPA, Montreal, Canada, p. A277.
- Chatterjee, A. and Dodson, C.T.J. and Whiting, P.** 1994. Formation and distributions of fibre length and flexibility. *Nordic Pulp Pap. Res. J.*, 9(2):120.
- Clark, J. d'A.** 1985. Wet fibre compactability. In "Pulp technology and Treatment for paper 2nd ed.", Miller Freeman inc., San Fransisco, p. 560.
- Davison, R. W.** 1972. The weak link in paper dry strength. *Tappi* 55(4):567.
- Fransson, P.-I., Karlsson, H. and Kastre, L.** 1992. Patent, US 533 1405.
- Fellers, C.** 1986. The significance of structure for the compression behaviour of paperboard. In "Paper structure and properties", Bristow, J. A. and Kolseth, P., eds. Marcel Dekker, Inc., New York, Vol 8, p. 281.
- Forgacs, O. L., Robertsson, A. A. and Mason, S. G.** 1958. The hydrodynamic behaviour of papermaking fibres. In "Fundamentals Paper-making Fibres", Bolam F. ed., Trans. Symp., Cambridge, UK, p.447.
- Forsström, J., Andreasson, B. and Wågberg, L.** 2004. Influence of pore structure on the strength of papers from unbleached kraft fibres. Accepted for publication in *Nordic Pulp Pap. Res. J.*
- Gärdlund, L., Forsström, J., Andreasson, B. and Wågberg, L.** 2003. Influence of polyelectrolyte complexes on the strength properties of papers made from unbleached chemical pulps. In "5th International Paper and Coating Chemistry Symposium", Montreal, Canada, p. 233.
- Howard, R. C. and Bichard, W.** 1991. The basic effects of recycling on pulp properties. In "1st Research forum on recycling", CPPA, Toronto, Canada, p. 81.
- Laivins, G. V. and Scallan, A. M.** 1993. The mechanism of hornification of wood pulps. In "Products of papermaking", Baker C. F. ed., Trans 10th Fund. Res. Symp., Oxford, UK, p. 1235.
- Mohlin, U-B.** 1975. Cellulose fibre bonding. *Svensk Papperstidning* 11:412.
- Nilsson, B., Wågberg, L. and Gray, D.** 2001. In "The science of papermaking", Baker C. F. ed., Trans 12th Fund. Res. Symp., Oxford, UK, p. 211.
- Page, D. H., Seth, R. S. and El Hosseiny, F.** 1985. Strength and chemical composition of wood pulp fibres. In "Papermaking Raw Materials", Punton, V. ed., Trans 8th Fund. Res. Symp., Oxford, UK, p. 77.
- Page, D. H.** 1969. A theory for the tensile strength of paper. *Tappi* 52(4):674.
- Scallan, A. M. and Tigerström, A. C.** 1992. Elasticity of the wet fibre wall: effects of pulping and recycling. *J. Pulp Paper Sci.* 18(5):188.
- Steadman, R. and Luner, P.** 1985. The effect of wet fibre flexibility of sheet apparent density. In "Papermaking Raw Materials", Punton, V. ed., Trans. 8th Fund. Res. Symp., Oxford, UK, p. 311.
- Stratton, R. A. and Colson, N. L.** 1990. Dependence of fibre/fibre bonding on some papermaking variables. *Mat. Res. Soc. Symp. Proc.* 197:173.
- Stone, J. E. and Scallan, A. M.** 1965a. A study of cell wall structure by nitrogen adsorption. *Pulp Pap. Mag. Canada.* 66(8):T407.
- Stone, J. E. and Scallan, A. M.** 1965b. Influence of drying on the pore structure of the cell wall. In "Consolidation of the paper web", Bolam F. ed., Trans Symp., London, UK, p.145.
- Stone, J. E. and Scallan, A. M.** 1968. The effect of component removal upon the porous structure of the cell wall of wood. Part III. A comparison between the sulphite and kraft process. *Pulp Pap. Mag. Canada.* 69:T288.
- Tam Doo, P. A. and Kerekes, R. J.** 1982. The flexibility of wet pulp fibres. *Pulp Pap. Canada.* 83(2):T37.
- Torgnysdotter, A. and Wågberg, L.** 2003. Study of the joint strength between regenerated cellulose fibres and its influence on the sheet strength. *Nordic Pulp Pap. Res. J.* 18(4):455.
- Torgnysdotter, A. and Wågberg, L.** 2004. Influence of electrostatic on joint and paper strength. *Nordic Pulp Pap. Res. J.* 19(4):440.
- Wahlström, B.** 1988. An overview of web consolidation. CPPA annual meeting. B351-B379.
- Wågberg, L., Ödberg, L. and Glad-Nordmark, G.** 1989. Charge determination of porous substrates by polyelectrolyte adsorption. Part 1. Carboxymethylated, bleached cellulosic fibres. *Nordic Pulp Pap. Res. J.* 4(2):71.

Manuscript received October 14, 2004
Accepted January, 2005