Miscellaneous

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Refining gentleness – a key to bulky CTMP

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Abstract: Chemithermomechanical pulp (CTMP) is often used in middle layers of multiply paperboards due to its high bulk at specified strength. Such a CTMP should consist of well-separated undamaged fibres with sufficient bonding capacity. The basic objective of this work is to examine the effect of refining on bulk, taking into account conditions such as temperature, sulphonation, refining gap and refiner size. First stage CTMP made from Norway spruce (*Picea abies*) were produced in pilot and mill scale trials. Two new parameters, *Equivalent temperature related to softness* and *Refining gentleness* are introduced that take into account refining conditions as actual temperature, softening temperature, bound sulphonate content, refining gap and refiner diameter. The results show that bulk increases linearly with refining gentleness.

Keywords: bulk; mechanical pulping; refining gap; sulphonation; temperature.

Introduction

Chemithermomechanical pulps (CTMP) of both softwoods and hardwoods are often used in middle layers, as a mixture together with broke and softwood kraft pulp, of multiply paperboards due to their high bulk at specified strength. The present study emanated from a project where the key research challenge was to find ways to produce paperboards with higher bulk and with as good strength

properties as the standard material. The aim of the project was to find synergetic effects by joint studies in three different technology areas: chip refining, low consistency (LC) refining and fibre surface chemistry. In chip refining, the objective was to separate the fibres while preserving their natural fibre morphology as much as possible. This was achieved by optimizing conditions affecting wood chip softening (Persson et al. 2019) and using refiner segments giving favourable processing. The objective in LC refining was to improve fibre surface area and, if necessary, improve separation of fibres from one another while preserving the fibre stiffness as much as possible. This was achieved by gentle mechanical treatment of the fibre surface in a refiner equipped with fine-patterned fillings (Berg et al. 2021). Without a significant decrease in bulk, CTMP strength was then increased by introducing cationic and anionic functional groups together with an organic catalyst, enhancing fibre-to-fibre adhesion (Alimohammadzadeh et al. 2018, 2019).

Koran (1968) examined fracture surfaces by means of light and electron microscopy of wet wood pieces that were generated by tangential tensile failure at various temperatures. He found that the number of fibres that are broken (into two pieces) is an almost linear relation of temperature (40 % broken fibres at 25 °C and 2 % at 200 °C). May (1973) used this result to build a theory about “the origin of fibre length” in chip refining. He assumed that a wood chip needs to be disintegrated in a number of consecutive steps in order to be broken down into single fibres. In a numerical example, he calculated that maximum 40 % of the fibres remained unbroken at 100 °C. The maximum percentage of unbroken fibres could be calculated at any temperature between 25 and 200 °C. By using May’s theory, we calculated that maximum 92 % of the fibres remains unbroken at 200 °C, Figure 1. It should be pointed out though that in chip refining, fibres are primarily broken by shear and compression. Lai and Iwamida (1993) found that a large part of earlywood fibres was broken in shear testing of wood pieces at room temperature, but at sulphite treatment (corresponding to 91–93 % yield) fibre splitting and fibre cutting were reduced to a minimum. They also found similar results in refining experiments, i. e. that earlywood fibres from sulphonated chips were less broken.

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Figure 1: Percentage of unbroken fibres in a chip refiner. Calculated by following equations given by May (1973).

The softness of wet wood chips during refining is determined by temperature, degree of sulfonation and deformation rate. Attack and Heitner (1979) showed that the softening temperature of sulfonated black spruce decreased linearly with sulphonate content, $-25^{\circ}\text{C} / \% \text{ bound SO}_3^-$ which is equal to $-6.4^{\circ}\text{C} / (\text{gS/kg bd})$. Their experiments were performed in a torsion pendulum in an atmosphere of saturated water vapour at temperature between 20 and 130°C and with sulphonate contents up to 7.2 gS/kg . They explained the softening effect by water as replacement of crosslinking hydrogen bonds with weaker lignin to water linkages and that sulphonation continues the replacement of crosslinking hydrogen bonds (that are inaccessible to water) with weaker lignin to sulphonate linkages. The softening was not effected by pH in the interval 3.5 to 9.8. The softening temperature was determined as the temperature at which the internal friction (in damped oscillations of about 10 Hz) had a maximum. For water saturated wood it has been demonstrated that the elastic modulus follows the general time-temperature superposition principle which makes it possible to calculate the properties of the wood over a large velocity-temperature interval (Salmén 1984). It is thus possible to also predict the effects of higher deformation rate by shifting the temperature. This shift was found to be about -8°C per decade for radial compression (Becker et al. 1977).

Miles and May (1990) are recognised for the development of a mechanistic theory involving both process and design parameters. They defined refining intensity as specific energy per bar impact that was shown to be effected by input variables as refining gap, pulp consistency, production rate, steam pressure in/out, rotational speed and segment geometry. Their model made it possible to calculate the refining intensity, however their model includes many simplifications and unknown parameters. Miles and

May's model and improved models that involve computational fluid dynamics (Huhtanen et al. 2009) and entropy calculations (Karlström et al. 2008) were compared in a study by Engberg and Berg (2011). The fluid dynamical model and especially the entropy model fairly well predicted both the specific energy distribution and the local refining intensity distribution over the radius in a mill scale chip refiner (Backlund et al. 2003, Härkönen et al. 2003). However, it is cumbersome to include refining energy in the definition of refining intensity as refining energy is an output variable that is often optimised with regard to pulp properties e. g. bulk, which is highlighted in this paper.

Bulk is a macroscopic indicator of fibre characteristics such as flexibility (Steadman and Luner 1985) and collapse (Görres et al. 1993). Fibres with thick walls are normally stiff resulting in a bulky pulp but fibres with broken walls are easy to collapse giving lower bulk compared to corresponding fibres without broken walls. Thin-walled early-wood fibres are more prone to fibre splitting especially at high intensity first stage refining (Reme et al. 1999, Pöhler and Heikkurinen 2003, Pettersson et al. 2021). Also freeness and fines content show strong interactions on bulk (Strand 1987).

Based on the literature study above it can be concluded that well separated fibres with as much as possible preserved natural fibre morphology are likely to be achieved by lowering the refining intensity or increasing either the chemical treatment (to reduce the softening temperature) or temperature to soften the wood structure. The objective of the present study was to examine the effect of refining on bulk, taking into account refining conditions such as actual temperature, sulphonation, refining gap and refiner size. In order to widen the perspectives on what effects bulk also output variables such as strength properties, freeness and specific refining energy are given as reference.

Materials and methods

The raw material for all trials consisted of Norway spruce (*Picea abies*) chips (of which 30 % was sawmill chips) from BillerudKorsnäs Rockhammar mill. First stage CTMP were produced in pilot scale trials in November 2018 at Valmet Technology Center in Sundsvall and in mill scale trials in February 2019 at BillerudKorsnäs Rockhammar mill.

In the pilot scale trials, steamed chips were impregnated with sulphite at initial pH 9.6, preheated and then fed into a pressurized 20-inch single disk refiner OVP 20

Table 1: Pulp properties and refining conditions from pilot scale trials.

Bound sulphur (S) g/kg	Sulphite Na ₂ SO ₃ kg/bdt	Preheating temperature °C	Refining gap mm	Specific refining energy kWh/t	Bulk cm ³ /g	Tensile index Nm/g	Z-strength kPa	Shives content* %	Fibre length* mm	Freeness CSF ml
2.56	25	160	0.30	196	2.93	13.0	87.7	3.86	2.12	770
2.56**	25	160	0.15	597	2.40	27.7	203.9	1.34	1.94	734
2.80	25	140	0.30	365	2.94	15.0	103.4	3.27	2.10	758
2.80**	25	140	0.20	777	2.43	26.3	206.6	0.97	2.01	728
2.96	25	180	0.20	166	2.81	15.0	96.2	2.26	2.23	748
2.96**	25	180	0.05	522	2.24	29.5	284.7	0.75	1.54	671
3.80	50	140	0.30	284	2.97	12.7	105.0	9.23	2.14	763
3.80**	50	140	0.20	592	2.60	22.1	146.9	1.50	2.15	738
4.12	50	180	0.20	155	2.69	17.9	133.8	2.10	2.22	764
4.12**	50	180	0.05	517	2.15	34.1	311.4	0.97	1.69	708
4.39	50	160	0.30	163	3.05	13.6	94.1	7.14	2.17	766
4.39**	50	160	0.15	356	2.62	19.2	150.5	0.68	2.20	751

*Shives content and length-weighted average fibre length were measured using a PQM analyser at Valmet Technology Center in Sundsvall.

**Bound sulphur (S) content was measured at the lower refining energy for each setting of chemical charge and temperature and was supposed to be the same for higher refining energy.

Table 2: Pulp properties and refining conditions from mill scale trials.

Bound sulphur (S) g/kg	Bisulphite as Na ₂ SO ₃ kg/bdt	Refining peak temperature °C	Refining gap mm	Specific refining energy kWh/t	Bulk cm ³ /g	Tensile index Nm/g	Z-strength kPa	Shives content* mg/100 g	Fibre length* mm	Freeness CSF ml
1.1**	20	160	0.88	567	2.55	19.2	144.0	5547	1.83	737
1.1	20	166	0.54	797	2.34	27.9	198.8	1106	1.74	723
1.0**	20	161	0.97	521	2.54	18.9	135.4	4908	1.87	750
1.0	20	165	0.55	809	2.33	26.8	199.8	2304	1.91	728
2.4**	43	160	0.97	518	2.54	19.6	152.0	4256	1.88	751
2.4	43	165	0.57	788	2.34	27.9	205.9	2096	1.85	741
2.5**	43	154	0.95	563	2.45	21.8	148.8	2862	–	742
2.5	43	159	0.62	804	2.29	27.4	206.7	1573	–	736

*Shives content using Sommerville with 0.15 mm slots and length-weighted average fibre length using PulpEye pulp analyser were measured at BillerudKorsnäs Frövi. **Bound sulphur (S) content was measured at the higher refining energy for each setting of chemical charge and temperature and was supposed to be the same for lower refining energy.

(Valmet). Different sulphite dosages, preheating temperatures and refining gaps were used according to Table 1. From the refiner, generated steam blew the pulp via a blow valve to an atmospheric cyclone where steam and pulp were separated. The pulp samples were collected in plastic bags placed under the cyclone. The sulphonation time, i. e. time from impregnation to sampling, was approximately 2 minutes.

For all trial points in the mill scale trials, steamed chips were impregnated with bisulphite and sodium hydroxide at initial pH 8.0. The residence time in the impregnator and the reaction vessel was typically 0.5 hour and the temperature was about 65 °C. After that, the chips were preheated to about 145 °C and then fed into a pressurized

68-inch single disk refiner RGP 268 (Valmet). The bisulphite dosages are presented as sulphite in Table 2, where also different refining peak temperatures and refining gaps are presented. Pulp samples were collected from the blow line via a custom-made sampler. The time from preheating to sampling, was approximately 6 minutes. For four trial points, extra bisulphite and sodium hydroxide was added to the refiner inlet. The residence time in the refiner was calculated to 1.5 s by a method described in Karlström et al. (2008).

Composite pulp samples were collected during a three-minute period and thereafter homogenized by hand for both pilot and mill scale trials, as recommended by Ferritsius et al. (2017). Any excess air in the bags was re-

moved and the bags were immediately sealed. Engstrand et al. (1985) have shown that the rate of sulphonation decreases about 10 times for every 20 °C decrease in temperature. To minimize chemical reactions (sulphonation) after sampling the bags were therefore stored at 5 °C overnight and then frozen and kept at –18 °C until the pulps were analysed.

Analyses

After hot disintegration (ISO 5263-3), tensile index (ISO 1924-2), z-strength (ISO 15754) and bulk (ISO 5270) were measured on handsheets of pulp (grammage 140 g/m²) formed with a Rapid Köthen sheet former (Rycobel, Deerlijk, Belgium, ISO 5269-2) at BillerudKorsnäs Frövi. Bound sulphur (S) content (SCAN-CM 57) and freeness (ISO 5267-2) were measured at MoRe Research in Örnsköldsvik.

Pulp properties and refining conditions of first stage CTMP from pilot and mill scale trials are shown in Table 1 and 2 respectively.

Results and discussion

First stage pulp samples taken from pilot and mill scale chip refiners with different refining gaps, refining temperatures and sulphur contents were compared with regard to handsheet bulk according to Table 1 and 2. As explained in the introduction, the softening temperature of softwood is lowered about 6.4 °C / (g S/kg) in the interval 0–7.2 (g S/kg). The softening temperature T_s can accordingly be expressed by Equation (1):

$$T_s = T_{S0} - 6.4S_b \quad (1)$$

where

T_{S0} = softening temperature (°C) at $S_b = 0$ g S/kg

S_b = bound sulphonate content (g S/kg)

For example, if $T_{S0} = 90$ °C and $S_b = 3.6$ g S/kg then according to Equation (1) the softening temperature T_s is 67 °C. If we further assume that the actual (refining) temperature is 100 °C, then according to Equation (1), the actual temperature is 33 °C above T_s but without sulphonation it would only be 10 °C above T_s . This can be understood as the material acts as if the actual temperature is increased when the sulphonate content is increased e. g. the elastic shear modulus at 100 °C and $S_b = 3.6$ g S/kg is the same as if the actual temperature would be 123 °C and

$S_b = 0$ g S/kg. Therefore, a measure of the equivalent temperature related to softness ET_s (°C) is proposed as:

$$ET_s = T + 6.4S_b \quad (2)$$

where

T = actual temperature (°C)

A graphical representation of Equation (2) is shown in Figure 2.

Figure 2: The equivalent temperature related to softness ET_s is affected by actual temperature and bound sulphonate content.

The measured bulk vs actual temperature and equivalent temperature related to softness on pulps from pilot scale trials according to Table 1 is shown in Figure 3a and b respectively. Mean value of standard deviations for bulk in this study were 0.06 cm³/g and this is indicated by error bars placed at regression lines at gap 0.20 mm and temperature 170 °C. Dashed lines connect points with same gap, ranging from 0.05 to 0.30 mm. In what way refining gap, actual temperature and sulphonate content is correlated to the bulk is not evident in Figure 3a. However by plotting bulk vs equivalent temperature related to softness, ET_s the overall picture is that refining with higher gap and higher ET_s results in higher bulk. It should be noted that the actual temperature inside the pilot refiner is not known. Therefore we use the preheating temperature as an approximation.

Figure 3b indicates that a combination of refining gap (higher refining gap is normally associated with lower refining intensity) and ET_s may be able to be described in terms of gentle or harsh refining, which are old expressions used by e. g. Härkönen et al. (2003). We therefore propose a new quantity, the refining gentleness G , as equivalent temperature related to softness times (g/D) defined by Equation (3).

$$G = ET_s g/D \quad (3)$$

Figure 3: Pilot trials performed at different bound sulphate contents, S_b . Bulk vs a) Actual temperature and b) Equivalent temperature related to softness.

where

g = refining gap (m)

D = refiner diameter (m)

One reason why the gap is normalized with refiner diameter is for time being to make the gap dimensionless. Thereby we also get a more understandable unit of refining gentleness G i. e. °C.

However, there are also some physical reasons for having D in the denominator:

- A larger refiner diameter is associated with higher refining intensity as it provides greater centrifugal force, but it also provides greater relative speed between the refiner plates, which means that less axial load is needed to maintain the same power. This reduces radial friction force and reduces residence time (Miles 1990).
- Härkönen and Tienvieri (2001) stated that refining intensity is linearly (inversely) dependent on g/D . Their calculations are thoroughly recapitulated in Engberg and Berg (2011).

The measured bulk vs refining gentleness on pulps from pilot scale trials is shown in Figure 4a and it appears that bulk increases linearly with refining gentleness. Corresponding figures from mill scale trials are also shown in Figure 4a. Interestingly, the calculated refining gentleness for mill scale trials is in the same order of magnitude as for those in pilot scale although conditions as refiner size and refining gap differ a lot; e. g. at bulk $2.4 \text{ cm}^3/\text{g}$ the calculated refining gentleness is 0.070 and 0.044 °C for mill and pilot scale trials respectively. However, Equation (3)

is a first straightforward approach to characterize refining gentleness. Most likely, additional input variables as e. g. production rate and segment pattern (Kure et al. 2000, Sandberg et al. 2018) could be incorporated in Equation (3) in order to improve its precision. It could also be reasonable to normalize the gap with the radial position at peak temperature in the refining zone. However, that position is varying with refining conditions (Karlström et al. 2008) and therefore the refiner diameter was used.

In present study it was also found that freeness correlated with bulk as shown in Figure 4b. Freeness is a measure of pulp drainability which is affected by output variables as e. g. shives, fines content, fibre length and fibre characteristics as e. g. flexibility and collapsibility. As expected, also tensile index and z-strength correlate with bulk as shown in Figure 4c and 4d respectively. Future challenges are to find more precise approaches to model handsheet properties as bulk with sets of input and output variables.

Conclusions

First stage chemithermomechanical pulp (CTMP) from Norway spruce were produced in pilot and mill scale trials. A number of pulp samples with different refining gaps and bound sulphur contents were compared with regard to handsheet bulk.

Two new quantities, equivalent temperature related to softness and refining gentleness are introduced. ET_s takes into account actual temperature, softening temperature

Figure 4: Pilot and mill scale trials performed at different bound sulphonate contents, S_b . (a) Bulk vs Refining gentleness (b) Bulk vs Freeness (c) Tensile index vs bulk and (d) Z-strength vs bulk. The symbol within parentheses is considered as an outlier and is therefore excluded from calculation of regression line.

and bound sulphonate content. Refining gentleness takes into account ET_S , refining gap and refiner diameter. Bulk was shown to increase linearly with refining gentleness in pilot scale trials and a linear relationship close to that found in pilot trials was also found in mill scale trials. The new quantity refining gentleness is therefore believed to be a versatile tool in research and process development in order to achieve bulky CTMP.

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Conflict of interest: The authors declare no conflicts of interest.

References

- Alimohammadzadeh, R., Osong, S.H., Dahlström, C., Cordova, A. (2018) Scalable improvement of the strength properties of chemimechanical pulp fibers by eco-friendly catalysis. In: Proceedings, Int. Mech. Pulping Conf., Trondheim, Norway. session 2.3.
- Alimohammadzadeh, R., Osong, S.H., Rafi, A.A., Dahlström, C., Cordova, A. (2019) Sustainable surface engineering of lignocellulose and cellulose by synergistic combination of metal-free catalysis and polyelectrolyte complexes. Global Challenges 3(7):1900018.

- Atack, D., Heitner, C. (1979) Dynamic mechanical properties of sulphonated eastern black spruce. *Trans. Tech. Sect. (Can. Pulp Pap. Assoc.)* 5(4):TR99–TR108.
- Backlund, H.-O., Höglund, H., Gradin, P. (2003) Study of tangential forces and temperature profiles in commercial refiners. In: *Proceedings, Int. Mech. Pulping Conf., Quebec, Canada*. pp. 379–386.
- Berg, J.E., Hellstadius, B., Lundfors, M., Engstrand, P. (2021) Low-consistency refining of CTMP targeting high strength and bulk: effect of filling pattern and trial scale. *Nord. Pulp Pap. Res. J.* 36(1):33–41.
- Becker, H., Höglund, H., Tistad, G. (1977) Frequency and temperature in chip refining. *Paperi ja Puu* 59(3):123–130.
- Engberg, B., Berg, J.E. (2011) A comparative study of models describing high consistency refining. In: *Proceedings, Int. Mech. Pulping Conf., Xian, China*. pp. 96–100.
- Engstrand, P., Hammar, L.A., Htun, M. (1985) The kinetics of sulfonation reactions on Norwegian spruce. In: *Int. Symp. Wood Pulping Chem., Vancouver, Canada*. pp. 275–279.
- Ferritsius, O., Ferritsius, R., Hill, J., Karlström, A., Ferritsius, J., Eriksson, K. (2017) Process considerations and its demands on TMP property measurements—A study on tensile index. *Nord. Pulp Paper Res. J.* 32(1):45–53.
- Görres, J., Amiri, R., Grondin, M., Wood, J. (1993) Fibre collapse and sheet structure. In: *Products of Papermaking, Trans. Tenth Fund. Res. Symp., Oxford, Great Britain, Vol. 1*. pp. 285–310.
- Huhtanen, J.P., Karvinen, R., Vikman, K., Vuorio, P. (2009) Determination of freeness reduction by refining intensity definition based on fluid dynamical model. In: *Proceedings, Int. Mech. Pulping Conf., Sundsvall, Sweden*. pp. 209–212.
- Härkönen, E., Kortelainen, J., Virtanen, J., Vuorio, P. (2003) Fiber development in TMP main line. In: *Proceedings, Int. Mech. Pulping Conf., Quebec City, Canada*. pp. 171–178.
- Härkönen, E., Tienvieri, T. (2001) Energy savings in TMP pulping. In: *Proceedings, Int. Mech. Pulping Conf., Helsinki, Finland*. pp. 547–556.
- Karlström, A., Eriksson, K., Sikter, D., Gustavsson, M. (2008) Refining models for control purposes. *Nord. Pulp Paper Res. J.* 23(1):129–138.
- Koran, Z. (1968) Electron microscopy of tangential tracheid surfaces of black spruce produced by tensile failure at various temperatures. *Svensk Papperstidn.* 71(17):567–576.
- Kure, K.A., Sabourin, M.J., Dahlqvist, G., Helle, T. (2000) Adjusting refining intensity by changing refiner plate design and rotational speed: Effects on structural fibre properties. *J. Pulp Paper Sci.* 26(10):346–352.
- Lai, Y.Z., Iwamida, T. (1993) Effects of chemical treatments on ultra-high-yield pulping 1. Fiber separation. *Wood Sci. Technol.* 27(3):195–203.
- May, W.D. (1973) A theory of chip refining – The origin of fiber length. *Pulp Paper Mag. Can.* 74(1):70–78.
- Miles, K. (1990) Refining intensity and pulp quality in high-consistency refining. *Paperi ja Puu* 72(5):508–514.
- Miles, K.B., May, W.D. (1990) The flow of pulp in chip refiners. *J. Pulp Paper Sci.* 16(2):J63–J72.
- Persson, E., Norgren, S., Engstrand, P., Granfeldt, T., Johansson, M., Edlund, H. (2019) Spruce HT-CTMP revisited -- A high yield, energy efficient pulp for future products. In: *Proceedings, Fundamental Mech. Pulping Res. Seminar, Norrköping, Sweden*.
- Pettersson, G., Norgren, S., Engstrand, P., Rundlöf, M., Höglund, H. (2021) Aspects on bond strength in sheet structures from TMP and CTMP—a review. *Nord. Pulp Pap. Res. J.* 36(2):177–213.
- Pöhler, T., Heikkurinen, A. (2003) Amount and character of splits in fibers cell wall caused by disc refining. In: *Int. Mech. Pulp. Conf., Quebec, Canada*. pp. 417–423.
- Reme, P.A., Johnsen, P.O., Helle, T. (1999) Changes induced in early- and latewood fibres by mechanical pulp refining. *Nord. Pulp Pap. Res. J.* 14(3):256–262.
- Sandberg, C., Nelsson, E., Engberg, B.A., Berg, J.E., Engstrand, P. (2018) Effects of chip pretreatment and feeding segments on specific energy and pulp quality in TMP production. *Nord. Pulp Pap. Res. J.* 33(3):448–459.
- Salmén, L. (1984) Viscoelastic properties of in situ lignin under water-saturated conditions. *J. Mat. Sci.* 19(9):3090–3096.
- Steadman, R., Luner, P. (1985) The effect of wet fibre flexibility on sheet apparent density. In: *Papermaking Raw Materials, Trans. Eighth Fund. Res. Symp., Oxford, Great Britain*. pp. 311–337.
- Strand, B.C. (1987) Factor analysis as applied to the characterization of high yield pulps. In: *Proceedings, TAPPI Pulping Conf., Washington, DC, USA*. pp. 61–66.