The Elongation Potential of Paper – How Should Fibres be Deformed to Make Paper Extensible?

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Elongation at failure is an important but underrated functional property of paper. Traditionally, elongation has been of specific importance for sack and bag paper grades. Mechanical treatments at high consistency are known to induce fibre deformations that contribute to the elongation of paper. However, it is not clear to what extent different fibre deformations can improve the elongation of paper. The aim of this work was to investigate the influence of three mechanical treatments on fibre and paper properties. The wing defibrator, the E-compactor, and the Valley beater were used for treating chemical softwood pulp. It was found that the type and intensity of mechanical treatments significantly affect the formation of fibre deformations, and thus the resulting properties of paper. The combination of high-consistency wing defibrator treatment and subsequent low-consistency valley beating provided paper with high elongation potential and good strength properties without impairing the dewatering properties.

Keywords: Elongation; Fibre deformations; Microcompressions; Shrinkage; Tensile strength

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INTRODUCTION

The mechanical properties of paper have been the subject of research since the rise of modern papermaking. Conventionally, tensile strength has been the primary target of improvement, while the other properties have been somewhat underrated. The elongation of paper is one of these underrated properties. In principle, elongation is the ability of material to increase its linear length under the action of external mechanical forces; the increase in the linear length is attributed to elastic and plastic deformations (Levlin and Söderhjelm 1999). This property increases the tensile energy absorption (TEA) potential of paper, which is defined as the integral of the tensile force and specimen elongation up to the point of failure, and is important for runnability of the web on the paper machine and in the printing house (Hristopulos and Uesaka 2002; Uesaka 2005; Deng *et al.* 2007), and for converting operations of paper and paperboard (Gärd 2002; Post *et al.* 2011; Östlund *et al.* 2011). Elongation of paper is also one of the central components of formability of paper-based materials (Vishtal and Retulainen 2012). The elongation potential of paper relies on three principal factors: properties of single fibres, the character of interfibre bonds between them, and the structure of the fibre network formed in the papermaking and converting processes (Dumbleton 1972; Page *et al*. 1985; Seth 1996; Welsh 1965). However, when the fibres have sufficient bonding, the elongation of a typical fibre network is primarily dependent on the single-fibre properties

(Seth 2005). Mechanical treatments of fibres at high consistency are known to induce fibre deformations that contribute to the elongation potential of the paper (Page *et al.* 1985, Seth 2005). Gentle laboratory beating at low consistency tends to straighten and lengthen fibres, reducing fibre deformation (Mohlin *et al* 1996; Seth 2005; Seth 2006). The combination of the high- and low-consistency refining is also known as a method to improve the elongation and tensile energy absorption of the paper at low airflow resistance (Sjöberg and Höglund, 2005 and 2007). This approach is used for production of sack and bag grades of paper in the industry. Also, compressive treatment at high consistency has been shown to be a potential fibre treatment to improve strength properties of paper. It causes different types of deformations in axial and transverse dimensions of fibres (Hartman 1985; El-Sharkawy 2008). However, there is still a lack of information in scientific literature on the subject of how mechanical treatments of different type and intensity affect the fibre deformations and the stress-strain properties of paper, and how the other essential paper properties are affected.

The influence of the mechanical treatments with three different devices, the wing defibrator (high consistency, HC), a compressive E-compactor (HC), and a Valley beater (low consistency, LC), on fibre and paper properties was investigated in this work. The combination of HC wing defibrator treatment and subsequent LC Valley beating was also studied. The effect of these treatments on fibre properties and zero-span tensile strength has been reported in a recent publication (Zeng *et al*. 2012).

EXPERIMENTAL

Materials

The fibre raw material used in the study was first-thinning bleached pine kraft pulp obtained as pulp sheets from the Pietarsaari mill of UPM-Kymmene. The chemical composition and fibre properties of the first-thinning pulp are quite close to those of conventional once-dried softwood market kraft pulps.

Methods

Mechanical treatments

Three different mechanical devices were used to treat the fibres: the wing defibrator (HC), the E-compactor (HC), and the Valley beater (LC). Figure 1 shows schematic illustrations of the wing defibrator and E-compactor devices.

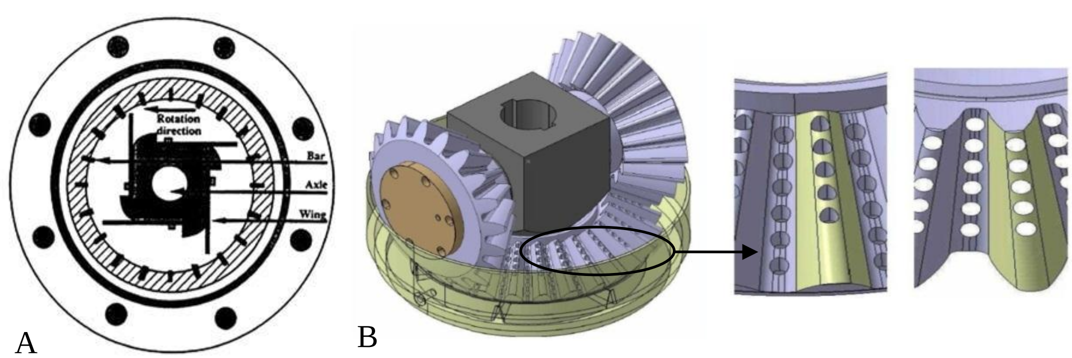

Fig. 1. Schematic illustrations of the wing defibrator (A) (Sundström *et al.* 1993) and the E-compactor (B)

Wing defibrator treatment

The wing defibrator is a high-intensity mixer fitted with four rotating blades; its primary utilization is in the preparation of mechanical pulp (Sundström *et al.* 1993). Each batch of 150 g (oven-dry) pulp was adjusted to a consistency of approximately 35% before the mechanical treatment. The rotation speed was 750 rpm, and the gap between the blades and the stator bars was 1 mm. There was a 20-minute pre-heating period. The jacket and chamber of the wing defibrator were heated by direct streaming. The condensate from the heating steam decreased the consistency of the pulp during the pre-heating phase. The conditions of the wing defibrator treatment are summarized in Table 1. The pure heating treatment without a mechanical treatment took place in an oil bath under similar conditions

Table 1. Conditions in the Wing Defibrator Treatment

Sample	SEC*, kWh/t	Temp. °C	DS** after treatment, %
Untreated/Preheated 110°C	0	110	35.6
B	243	110	25.6
C	297	110	21.4
D	418	110	21.6
E	657	110	22.1
F	1129	110	21.7
Untreated/Preheated 170°C	0	170	35.5
G	128	170	9.9
H	612	170	9.2

*Specific energy consumption, **DS-dry solids content

E-compactor treatment

The E-compactor (Fig. 1B) is a device with two rotating cogwheels that employs both compressive and hydraulic forces to press fibres through conical holes. It was developed at VTT Tampere. The fibres were treated at 30% consistency by passing them once or twice through the E-compactor with conical holes of 2 mm in diameter.

Valley beater treatment

The applied beating procedure was in accordance with the SCAN-C 25:76 method. Pulp measuring 360 g (oven-dried weight) was used for one batch in Valley beater and was diluted to the 23 L of total volume, giving a consistency of 1.57 g/L. The pulp was disintegrated in the beater without a load for 30 minutes. The disintegrated sample was defined as the "untreated fibres" sample. Then, pulp samples of 2 L were taken after 15, 30, 45, and 60 min of beating.

Combined high consistency (HC) and low consistency (LC) treatment

The combined HC and LC treatment included a wing defibrator treatment (WD) followed by a Valley beating (VB). The refining conditions for HC treatment are shown in Table 2, and LC beating was performed according to the SCAN-C 25:76. The SR number after the Valley beating was 23. The conditions used in the HC-refining are shown in the Table 2.

Table 2. The Conditions for HC Wing Defibrator Treatment

Parameter	Value
Refining gap	1 mm
Starting pulp consistency	30%
Temperature in refining	110°C
Preheating time	5 min
Rotation speed	750 rpm
Specific energy consumption	566 kWh/t

Fibre and pulp analysis

Fibre samples (approx. 0.1 g oven-dry mass) were taken for the automated fibre analysis with the STFI Fibermaster by Lorentzen & Wettre. Fibre parameters, including fibre length, fibre width, fibre curl, kinks, and fines content were analysed. The dewatering properties were characterised by the Schopper Riegler number (SR number) and the water retention value (WRV) in accordance with the ISO 5267-1 and SCAN-C 62:00 standards, respectively.

The fibre samples were unstained and observed under a light microscope (Olympus BX50) using transmitted light. The polarized mode was used for analysis, in which the angle positions of polarizer and analyser were varied.

A scanning electron microscope (SEM, LEO DSM 982 Gemini FEG-SEM, NORAN Instruments, Inc.) was used for inspecting the surface structure of the handsheets. Paper samples (*ca*. 10 mm×10 mm) were attached on carbon adhesive discs (12 mm) pressed on 12.5 mm aluminium stubs. A thin layer (ca. 10 nm) of platinum was sputter coated on each sample surface prior to analysis. The SEM analyses of the samples were conducted using an acceleration voltage of 1.0 keV or 2.0 keV.

Handsheet preparation

Handsheets were prepared according to SCAN-C 26. In addition to standard plate drying, a second set of handsheets were air-dried between two wire fabrics that had a gap of around 1 to 3 mm, which allows free shrinkage of the handsheets without excessive cockling or curling.

Paper properties analysis

The strength properties of the handsheets, including tensile strength, elongation, tensile energy absorption (TEA), and tensile stiffness, were determined using a universal material-testing device (LR10K, LLOYD Instruments) in accordance with SCAN-P38. Light scattering coefficient of handsheets was determined in accordance with ISO-9416.

The procedure applied for shrinkage potential measurement can be described as follows: Handsheets were marked after wet pressing by making holes using a square plate with awls at each corner. The four punched holes defined a square with a known perimeter. After this, the handsheets were allowed to dry and shrink freely. The extent of shrinkage was calculated from the change of the perimeter using a high-resolution scanner and special software. Equation (1) was used for the calculation of the shrinkage,

$$Shrinkage = \frac{L_w - L_d}{L_w} \times 100\% \tag{1}$$

where L_w is the perimeter of the rectangular perimeter in the handsheet before drying and L_d is the perimeter of the dried handsheet.

RESULTS AND DISCUSSION

Fibre Properties

The effects of the wing defibrator and Valley beater treatment on the fibre properties and dewatering properties of pulp can be found in a previous publication (Zeng *et al.* 2012). The treatment of pulp using the E-compactor device brought about drastic changes in the fibre structure, which can be seen in Table 3.

Table 3. Fibre Parameters, Water Retention Value, and Drainage Properties of E-Compactor Treated Pulp

Sample	Fibre length, mm	Fibre width, µm	Shape factor, %	Kink/mm	Fines,%	SR number	WRV, g/g
Untreated	2.05	29.6	82.1	0.69	6.0	14	1.03
1 pass	1.25	30.6	82.8	0.93	8.5	8	1.16
2 passes	1.13	30.9	82.9	0.97	10.5	9	1.27

E-compactor results in Table 3 show that fibre length was reduced by as much as 40% even though the fibres were passed through the E-compactor only once. Fibre width was increased because of the flattening and collapse of fibres. Kinks were induced to fibres during the E-compactor treatment. It can be concluded that E-compactor treatment caused severe fibre deformations and damage, such as fibre flattening, squashing, and fibre cutting.

The influence of HC wing defibrator treatment and subsequent LC valley beating on the fibre properties can be seen in the Table 4.

Table 4. The Effect of HC Wing Defibrator Treatment and Subsequent LC Valley Beating on Fibre Parameters and Drainage Resistance

Sample	Fibre length, mm	Fibre width, µm	Shape factor, %	Kink/mm	Fines, %	SR number
Untreated	2.05	29.6	82.1	0.69	6.0	14
HC wing defibrator	1.90	30.0	79.6	0.87	8.5	14
HC wing defibrator +LC Valley beater	1.97	29.2	85.8	0.31	9.8	23

In Table 4 it can be clearly seen that the HC wing defibrator treatment created deformations (curl and kinks) in the fibres, while the subsequent LC beating straightened the fibres, released fibre curl and kinks, and increased the swelling of the fibres. Fines content was increased by both of the mechanical treatments.

Polarized light microscopy was used for the evaluation of the fibre deformations caused by the different types of mechanical treatment. The emphasis in this study was on the identification and characterization of microcompressions in fibres. The polarized images allow for better observation of the changes in the fibre structure caused by the mechanical treatments. Figure 2 shows polarized images of the untreated, HC wing defibrator treated fibres, and combined HC wing defibrator and LC valley beater treated fibres.

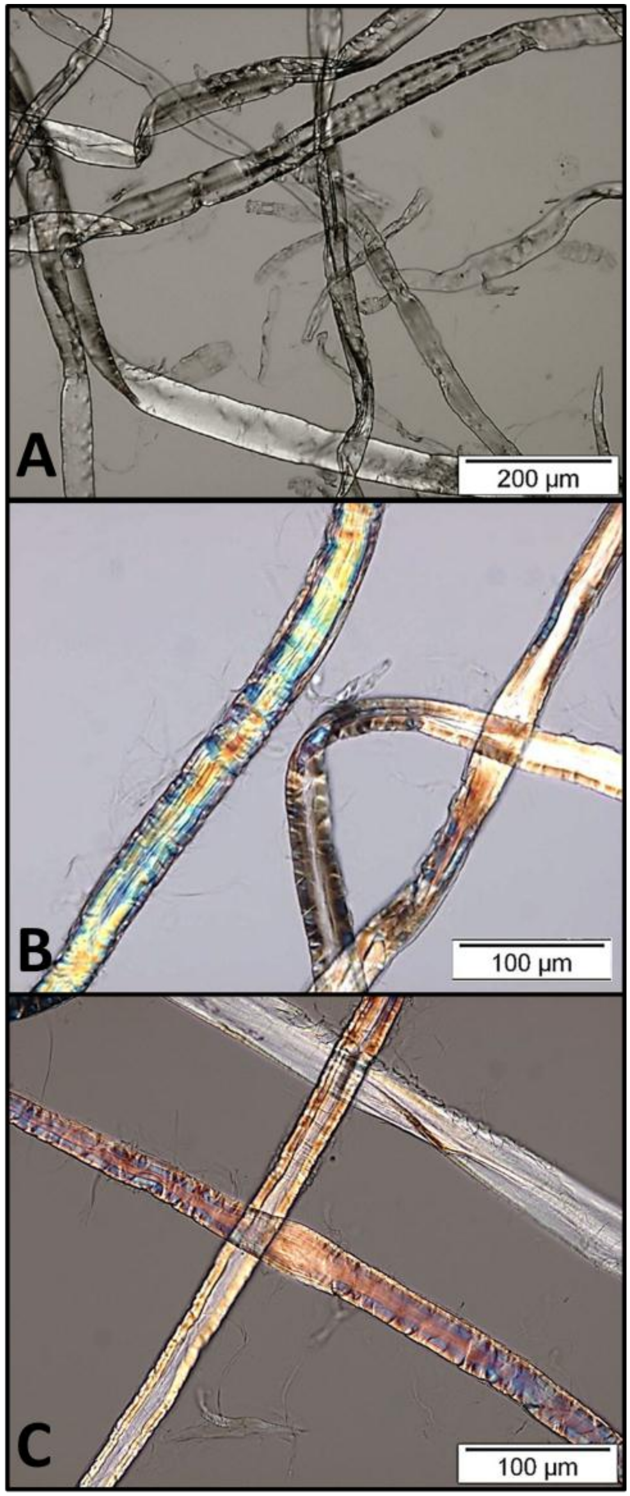

Fig. 2. Polarized (45° polarizer/90° analyser) images (A) untreated fibres, (B) high-consistency wing defibrator treated fibres, and (C) fibres after combined HC wing defibrator and LC Valley beater treatments

The microcompressions and dislocations can be observed as high-contrast lines perpendicular to the axis of the fibre (Thygesen and Ander 2005). Untreated fibres showed only some microcompressions, though dislocation zones, kinks, and curl were present. HC wing defibrator treated fibres showed more severe dislocations and also microcompressions. The combined HC wing defibrator and LC valley beater treated fibres tend to have less dislocation zones but also a considerable number of microcompressions could be seen. This suggests that microcompressions can be preserved well during the LC beating, even though LC beating is able to straighten fibres and release fibre curl and kinks, as previously mentioned.

Paper Properties

The properties of the restrained-dried and freely-dried handsheets made of wing defibrator treated fibres are summarized in Table 5a and 5b, respectively.

Table 5a. Handsheet (restrained drying) Properties from the Wing Defibrator Treated Pulp

Temp.,°C	SEC, kWh/t	Density, kg/m^3	Scattering coeff.,m^2/kg	Tensile index, Nm/g	Elongation, %	TEA index, J/g	Tensile stiffness, Nm/g
110	0	527	33.9	20.4	2.76	0.45	3695
	243	599	26.8	31.12	4.01	0.96	4008
	297	609	25.9	35.42	4.33	1.17	4372
	418	610	25.9	35.77	4.35	1.17	4206
	657	637	23.9	41.22	4.71	1.47	4937
	1129	644	23.3	47.14	4.83	1.70	5455
170	0	527	32.9	16.52	1.6	0.20	3512
	128	470	36.5	11.28	2.27	0.20	1986
	612	486	36.1	12.13	2.42	0.23	2080

Table 5b. Handsheet (free drying) Properties from the Wing Defibrator Treated Pulp

Temp.,°C	SEC, kWh/t	Density, kg/m^3	Tensile index, Nm/g	Elongation, %	TEA index, J/g	Tensile stiffness, Nm/g	Shrinkage, %
110	0	500	17.59	5.35	0.72	2067	2.91
	243	538	25.43	7.38	1.35	1956	3.06
	297	517	27.12	7.68	1.45	1875	3.73
	418	522	29.76	8.32	1.71	1989	3.48
	657	539	32.94	9.05	2.02	2040	4.17
	1129	558	37.58	8.76	2.17	2219	4.08
170	0	502	14.12	3.17	0.34	2013	2.24
	128	461	8.51	4.48	0.3	999	3.2
	612	477	10.24	5.33	0.43	1120	3.54

For the handsheets dried under restraint, the density increased and the light scattering coefficient decreased with increasing specific energy consumption in wing defibrator treatment at 110°C. This reduction in light scattering coefficient indicates that there was an increase in the number and area of fibre bonds in the sheets. Tensile index, TEA, and tensile stiffness all increased with the increase in specific energy consumption (110°C). Preheating of pulp caused a decrease in paper density, probably due to the reduced fibre flexibility caused by hornification type of effect (Zeng *et al.* 2012). Preheating of pulp at 170°C had a clear negative effect on the tensile strength, tensile stiffness, and elongation of the sheet. At 110°C the elongation of freely dried handsheets was as high as 9%. Although a rather high amount of refining energy was needed to reach that level, the SR number was as low as 15 (Zeng *et al.* 2012).

Table 6. Handsheets (restrained drying and free drying) Properties of E-Compactor Treated Pulp

Drying type	Samples	Density, kg/m^3	Scattering coeff., m^2/kg	Tensile index, Nm/g	Elongation, %	TEA index, J/g	Tensile stiffness, Nm/g	Shrinkage, %
Restrained drying	Untreated	513	34.7	18.05	2.15	0.31	3098	-
	1 pass	535	26.9	17.91	2.22	0.29	3038	-
	2 passes	516	25.3	18.77	2.25	0.32	3270	-
Free drying	Untreated	500	34.6	15.89	4.23	0.51	1939	2.52
	1 pass	480	26.5	14.24	4.01	0.43	1506	3.24
	2 passes	465	25.6	14.41	4.19	0.45	1461	3.36

Mechanical properties of the paper made of fibres that had been treated using the E-compactor can be found in Table 6. The stress-strain properties of the handsheets did not essentially improve with E-compactor treatment, even though the treatment caused severe damage and shortening of fibres as previously mentioned. The negative effects were partially covered by the improved bonding and sheet density caused by the fibre flattening and increased amount of fines in pulp. In general, the increased number of fibre kinks caused by E-compactor treatment did not contribute to any improvements in strength properties of paper. It seems that the applied compressive E-compactor treatment, in addition to weakening fibres, also caused excessive deformations that were not able to improve elongation or bring any other benefits for the paper. Thus, the E-compactor treatment does not warrant any further analysis or discussion.

Table 7. Properties of Handsheets (restrained drying and free drying) Prepared from Valley Beaten Pulp

Drying type	Refining time, min	Density, kg/m^3	Scattering coeff. m^2/kg	Tensile index, Nm/g	Elongation, %	TEA index, J/g	Tensile stiffness, Nm/g	Shrinkage, %
Restrained drying	0	513	34.7	18.05	2.15	0.31	3098	-
	15	625	26.0	64.08	3.77	1.75	6613	-
	30	664	23.3	82.44	3.73	2.16	7587	-
	45	700	21.0	87.59	3.55	2.18	8247	-
	60	734	18.5	101.65	3.64	2.45	9382	-
Free drying	0	500	34.6	15.89	4.23	0.51	1939	2.52
	15	563	25.6	53.43	6.84	2.17	2880	3.15
	30	568	21.8	69.17	8.21	3.13	2568	3.93
	45	571	19.2	75.53	9.07	3.75	2637	4.89
	60	571	17.0	78.95	10.7	4.42	2167	5.88

The mechanical properties of the handsheets prepared from the pulp treated in the Valley beater are shown in Table 7. The density of paper increased and the light scattering coefficient decreased significantly with Valley beating. An increase in the tensile strength of handsheets can be explained by the improved interfibre bonding, as well as by the fact that in addition to the improved straightness, the fibres also have a better load-bearing ability in the fibre network. Extensive beating resulted in elongation of freely dried sheets as high as 10.7%. However, these improvements were associated with the strongly impaired drainage, which is indicated by the considerable increase of SR number. SR number was 79 for the 60 min beaten pulp (Zeng *et al.* 2012).

Table 8. Properties of Handsheets (restrained drying and free drying) Prepared from the HC Wing Defibrator and Subsequent Valley Beater Treated Pulp

Drying Type	Samples	Density, kg/m^3	Tensile Index, Nm/g	Elongation %	TEA Index, J/g	Tensile Stiffness, Nm/g	Shrinkage %
Restrained drying	Untreated	513	18.05	2.15	0.31	3098	-
	HC wing defibrator	446	21.49	3.88	0.59	2620	-
	HC wing defibrator + LC valley beater	598	64.95	4.50	1.92	5883	-
Free drying	Untreated	500	15.89	4.23	0.51	1939	2.52
	HC wing defibrator	383	18.01	7.47	0.91	1162	5.35
	HC wing defibrator + LC valley beater	466	51.32	9.91	2.83	1599	5.80

The data in Table 8 show the effects of combined HC wing defibrator treatment and LC Valley beating on the mechanical properties of the handsheets. HC wing defibrator treatment increased the elongation of paper but had only a small effect on the tensile strength. With the subsequent Valley beating, the load bearing ability of the fibres and extent of fibre-fibre bonding was greatly enhanced, which was indicated by the increased paper density and strongly improved strength.

SEM images of the handsheets

The SEM pictures of handsheet surfaces prepared from the pulps, which had been subjected to the different mechanical treatments, can be found in Fig. 3. The SEM-image of a handsheet prepared from untreated pulp (A), suggests that fibres were relatively stiff, less collapsed, and less conformable, but that some fibres had extensive dislocations. Images of wing defibrator treated fibres (B and C) suggest that the fibres were curlier and better bonded than the untreated ones. It is possible to observe damage and deformations in fibres that had been treated with the wing defibrator at 170ºC (Fig. 3D). The morphology of E-compactor treated fibres (Fig. 3E) differed remarkably from the morphology of untreated and wing defibrator treated fibres. E-compactor treatment caused fibre cutting and fibre damage in addition to extensive fibre deformations. The handsheets (Fig. 3F) from the combined HC and LC treatment show relatively straight and collapsed fibres with a high degree of fibre bonding and also relatively large dense areas in the sheet.

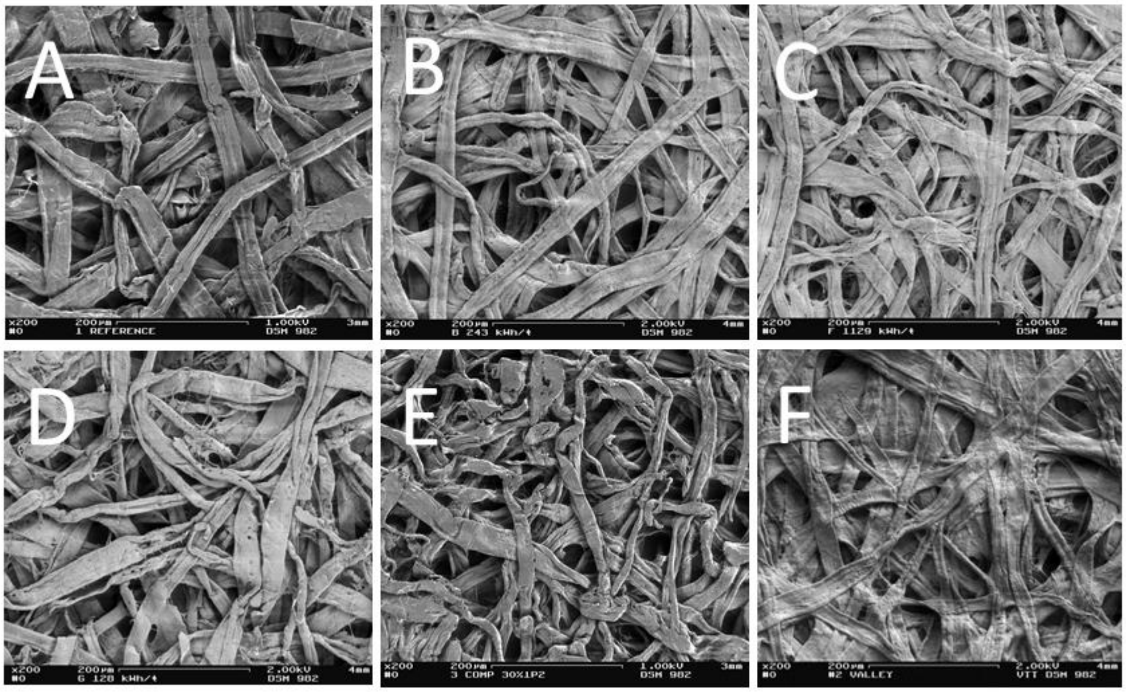

Fig. 3. SEM images of handsheets from different mechanical treatments; (A) Untreated reference handsheet; (B) wing defibrator treated with SEC of 243kWh/t, 110°C; (C) wing defibrator treated with SEC of 1129kWh/t at 110°C; (D) wing defibrator treated with SEC of 128kWh/t at 170°C; (E) E-compactor treated (30%1P2mm); (F) combined HC wing defibrator and LC valley beater treatment (150 g/m^2)

Factors affecting the elongation potential of paper

The elongation of paper varied according to the different mechanical treatments. When the handsheets were dried under restraint as shown in Fig. 4, the wing defibrator treatment (at 110ºC) provided fibres with the higher elongation potential than Valley beating but paper of lower tensile strength. The combined HC wing defibrator treatment and Valley beating provided high elongation potential, and at the same time, clearly higher tensile strength for the paper, in comparison with wing defibrator treated fibres.

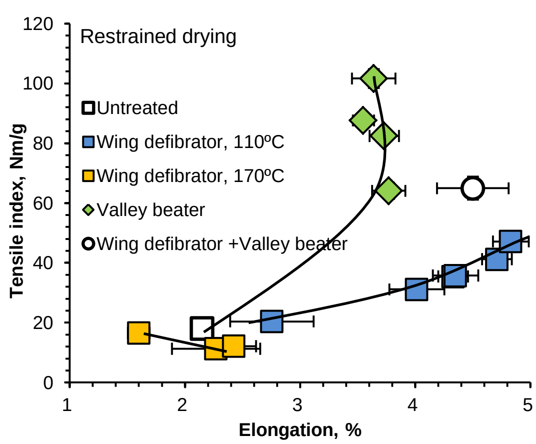

Fig. 4. Elongation versus tensile index of handsheets with restrained drying. The error bars show 95% confidence intervals.

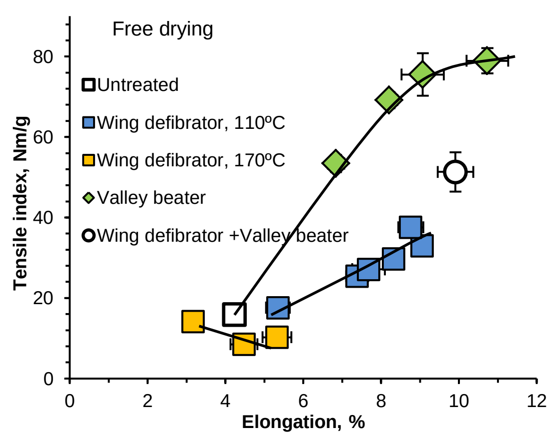

Fig. 5. Elongation versus tensile index of handsheets with free drying. The error bar shows 95% confidence intervals.

In the case of freely dried handsheets (Fig. 5.), Valley beating appeared to be a promising way to obtain high tensile strength and elongation properties of paper. HC wing defibrator treatment followed by Valley beating seemed to have better elongation potential at a certain value of tensile strength, compared with Valley beating.

It was expected that there would be a correlation between fibre deformations and elongation potential of handsheets, since the structure of the single fibres is one of the factors that determine the mechanical behaviour of the paper. However, the correlation between the degree of fibre curl and elongation of paper was found to be scattered (in Fig. 6) in the present work. In the initial stage of mechanical treatment, the elongation of handsheets improved with increasing fibre curl for HC wing defibrator treatment (at 110°C), but even with reducing fibre curl for Valley beating. This result implied that increasing fibre curl is not necessarily leading to improved elongation. The fibre deformations contributing to elongation were probably smaller scale deformations than fibre curl, such as microcompressions. The reduction of fibre curl probably contributes to better stress distribution in paper, which improved both paper strength and elongation.

The density of the paper has a strong influence on the stress-strain properties of paper, since the density is directly related to the amount of fibre-fibre contacts. Figure 7 shows that paper elongation generally increased with increasing sheet density for HC wing defibrator treated fibres (110°C). The extent of fibre bonds determined the elongation potential of paper for HC wing defibrator treated fibres. For Valley beating, paper elongation was increased with the sheet density up to a certain point, after which the sheet density continued to increase, and the elongation stayed constant. These results suggest that fibre flexibility and bonding are, to a certain point, beneficial for elongation of the sheet.

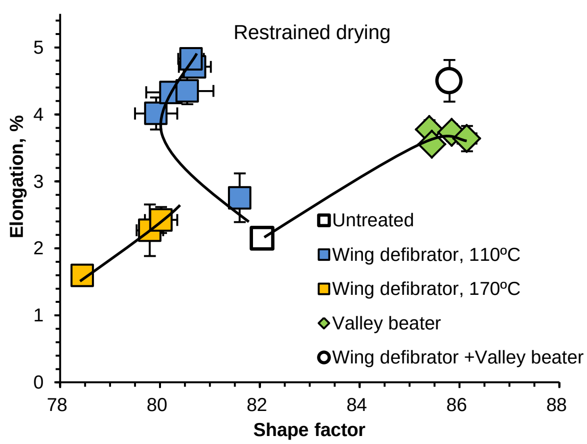

Fig. 6. Effect of shape factor on the elongation of handsheets with restrained drying. The error bars show 95% confidence intervals.

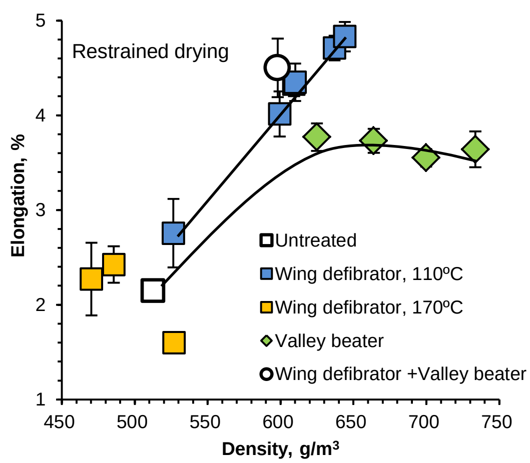

Fig. 7. The effect of the density on the elongation of the handsheets (restrained drying). The error bars show 95% confidence intervals.

The Schopper Riegler number (SR number) can be used for estimation of the dewatering ability of pulp, and it was correlated with the degree of swelling of fibres and also with the fibre flexibility and amount of fines. The relation between the elongation of the freely dried handsheets and SR number of the pulp is shown in Fig. 8. The elongation of handsheets (freely dried) was increased continuously with increasing SR-number due to Valley beating. For HC wing defibrator treatment (110°C), the elongation was increased even though SR number did not change greatly. Generally, HC wing defibrator treatment provided higher elongation than Valley beating when compared at a certain drainage resistance level. The combined HC wing defibrator and LC Valley beating achieved high elongation and good strength, while drainage resistance and fibre swelling were on a relatively low level.

The degree of swelling affects the drying shrinkage of handsheets due to the higher shrinkage of fibres. Water retention value of the pulp can be used for the estimation of the changes in the swelling of fibres. The influence of the water retention of the pulp on the elongation of restrained and freely dried paper in the case of wing defibrator treatment is shown in Fig. 9. There was a linear correlation between the WRV of pulp and the elongation of handsheets, and this correlation was stronger in the case of the restrained dried handsheets. However, one might say that the WRV was influencing the elongation of freely dried handsheets to a higher extent, since the trend line was steeper. This can be explained by the drying shrinkage effect, because shrinkage of paper during drying is greatly dependent on the degree of swelling of the fibres.

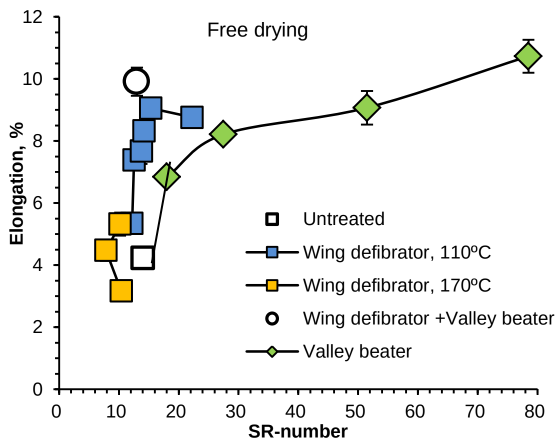

Fig. 8. Effect of drainage property on the elongation of handsheets (free drying). The error bars show 95% confidence intervals.

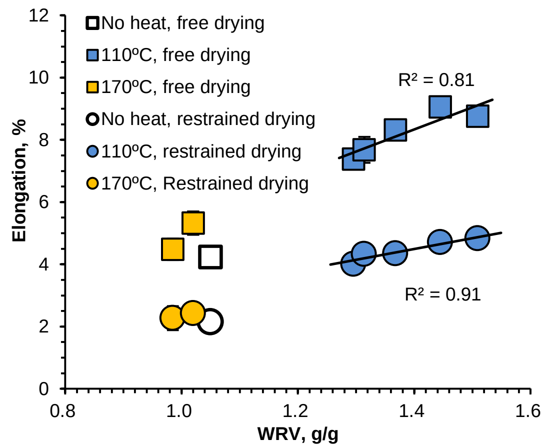

Fig. 9. Effect of water retention value of pulp on the elongation of the handsheets in the case of wing defibrator treatment. The error bars show 95% confidence intervals.

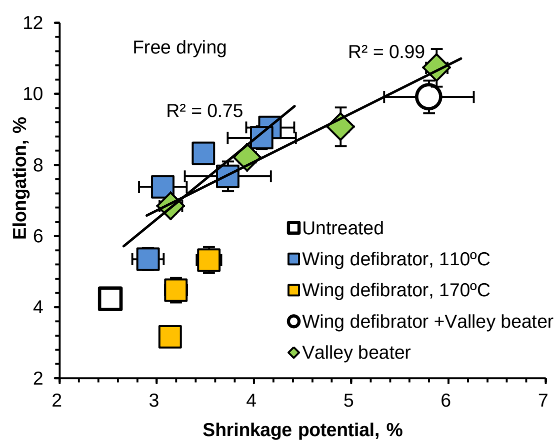

Fig. 10. Correlation between the shrinkage potential and elongation of handsheets (free drying). The error bars show 95% confidence intervals.

Shrinkage potential of the handsheet depends on fibre swelling and subsequent fibre shrinkage, on the number of fibre bonds where the fibre shrinkage is converted to axial shrinkage of neighbor fibres, and on the axial stiffness of the “neighbor” fibres (Retulainen *et al.* 1998). A linear correlation between shrinkage and elongation could be observed for wing defibrator treated fibres and Valley beaten fibres, as shown in Fig. 10. When the handsheets were dried without any restraint, shrinkage potential was the crucial factor determining the elongation of sheets. However, we could speculate that HC wing defibrator treatment contributes to increased shrinkage through a different mechanism than Valley beating. Valley beating probably increases the shrinkage and bonding of fibres, whereas wing defibrator treatment reduces the axial stiffness of the fibres.

CONCLUSIONS

First-thinning bleached pine kraft fibres were treated using selected mechanical treatments. The development of the elongation of freely and restrained-dried paper was evaluated through the fibre and fibre network properties. The results indicated that high consistency wing defibrator treatment caused curl, kinks, dislocations, and microcompressions in the fibres. Among them, small scale deformations, such as microcompressions have an important role in the elongation potential of sheets and can be preserved in subsequent Valley beating, which tends to straighten the fibres and release kinks and dislocated zones. Increasing fibre curl does not necessarily lead to improved paper elongation due to the reduced load-bearing ability of curly fibres in the fibre network. The elongation of the freely dried and restrained dried paper is dependent on different factors. In the case of freely dried paper, the shrinkage potential is the dominant factor; while in the case of restrained dried paper, the fibre wall morphology has a crucial role. The combined high consistency wing defibrator treatment and subsequent low consistency Valley beating was found to be the best strategy to produce paper with a high level of elongation, maintaining high tensile strength and good dewatering properties.

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