Chapter 4

Effect of Press-Drying Parameters on Paper Properties

Ahmed Koubaa and Zoltan Koran

Additional information is available at the end of the chapter

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Abstract

This study investigates alternatives that can improve the internal bond strength (IBS) of paper by pulp refining and paper press-drying (PD). The improvement mechanisms of IBS and their impact on the strength development of high-yield pulps are discussed. All experiments were conducted using a factorial design where the factors were four pulp types (one spruce thermomechanical (TMP) and three chemi-thermomechanical (CTMP) from spruce, birch, and aspen), three refining levels, three PD temperatures and three pressures. The effects of these treatments on the physical and mechanical properties of paper were studied using an analysis of variance. Refining changed the fibre surface, thereby promoting mechanical adhesion. PD temperature softened the fibres and changed their surface chemistry, while PD pressure improved the contact area between fibres. These changes led to an important improvement in IBS which explained, to a large extent, the variations in paper properties. Compared to air-dried paper, PD paper showed much higher properties for most tested pulps at all refining levels. These results were due to the increase in bonded areas. PD at 175°C substantially improved the wet tensile strength of paper due to the flow of lignin on the fibre surface, which protects the hydrogen bonds from moisture.

Keywords: press-drying, paper properties, internal bond strength, fibre properties, surface chemistry

1. Introduction

Fibre morphology, strength and adhesion are the main factors controlling paper strength [1–12]. Chemical composition is closely related to fibre strength and is an important factor in paper strength development [3, 5]. Among paper strength properties, tensile strength and tearing resistance are the most studied properties due to their importance during conversion and in end-use [1–12]. **Table 1** summarises the impact of the different fundamental fibre properties on paper tear, tensile and burst strength.

Properties	Morphological [1, 7–14]				Chemical [5, 15–22]			Mechanical [1–7, 15, 23–32]		
Strength Properties	**Length**	**Wall thickness**	**Coarseness**	**Microfibril angle**	**Cellulose**	**Lignin**	**Hemicelluloses**	**Strength**	**Flexibility**	**Adhesion**
Tear strength	+	–	–	–	+	–	+	+/–	–	+
Burst strength	+	–	–	–	+	–	+	+	+	+
Tensile strength	+	–	–	–	+	–	+	+	+	+

Table 1. Effect of increasing fundamental fibre properties on the development of the strength properties of paper.

The variation in tearing resistance is complex and researchers have carried out an impressive number of studies to understand this variation [2, 3, 5–8, 10]. Fibre length, strength and bonding are the main controlling factors. Although no clear relationship has been reported between tear index and fibre coarseness, in well-bonded sheets the tear index has been found to be higher in sheets with coarser fibres [6, 7].

Fibre length is an important factor in tearing resistance. Longer fibres improve tearing resistance, particularly for weakly bonded sheets [3, 6–8, 10–13]. However, fibre length is less important in well-bonded sheets having strong interfibre adhesion since sheet failure caused by tear is then controlled by the strength of the fibres [6, 7]. The tearing resistance is proportional to the square of fibre strength when fibre strength is modified without affecting other fibre properties or sheet structure [6, 7]. However, this does not necessarily imply that fibre failure is the prevailing mechanism of energy dissipation [8]. The elastic energy released when fibres or bonds fail depends on the load within the fibres and on the number of failures. All these entities are related to fibre strength.

The variation in the tensile strength of paper is controlled mainly by the internal bond strength. Indeed, several studies have reported clear positive linear relationships between the tensile strength and the internal bond strength [4, 25–27]. Fibre strength, morphology and coarseness are also important for the tensile strength development of paper. For example, the Page Equation [1] predicts the tensile strength from fibre properties including length, strength coarseness, fibre transverse perimeter, bond area and bond strength. This equation is widely recognised for predicting the tensile strength of paper. Clark [3] developed a statistical model to predict all paper properties from fibre properties. These models indicate the importance of the fibre properties for the development of paper strength.

The extent of fibre-to-fibre bonding is also important in determining paper strength. Improving this property is known to have beneficial effects on most sheet strength properties, except for tearing resistance. For the latter, the relationship is complex since it varies with the degree of interfibre bonding. **Figure 1** illustrates the general model that describes the variation of tear strength with the internal bond strength of paper. In poorly bonded sheets, increasing bonding strength improves the tearing resistance. However, in well-bonded sheets, higher bonding strength reduces the tearing resistance [3, 6–8]. This variation makes developing a model to predict the tear index from fibre properties difficult. Some attempts were made in the past to characterize this relationship using several approaches [7]. In general, fibre dimensions and physical properties are varied by either pulping different woods or fractioning a pulp. The paper properties from these pulps are generally modified by beating. The dependence of paper properties on fibre properties is then studied by statistical methods. This approach led to some good correlations, but there were no clear relationships because fibre properties are modified by beating and are generally interdependent.

The abovementioned studies have led to an excellent understanding of the tear mechanism and explained the role of each fibre property in the development of tearing resistance. For example, Page [6] elucidated the tear strength mechanism and determined the extent of its dependence on each fibre property by studying the effect on each property separately. Later, a model was developed [2] to describe the tearing energy of rupture of softwood pulps using

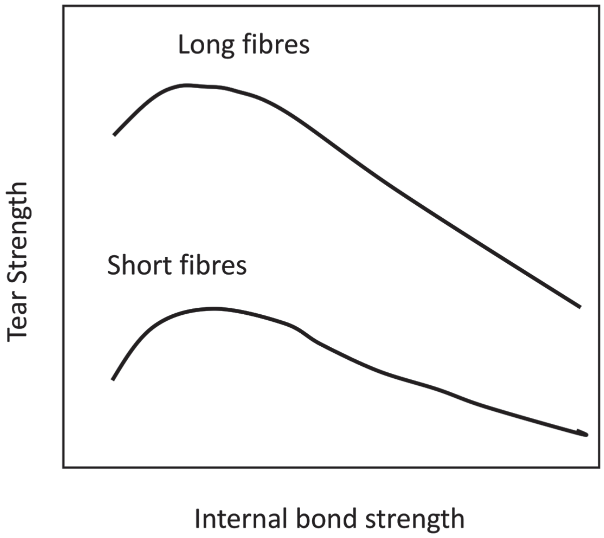


Figure 1. Typical model of variation of the tear index with fibre length and internal bond strength [6, 7].

the Page Equation [1]. However, most of these studies dealt with chemical pulps, particularly those made from softwoods. Only few studies dealt with the role of fundamental fibre properties of high-yield pulps [4, 12, 15, 28–30]. Moreover, few reports directly studied the effects of interfibre bonding [4, 15, 25–27, 30–32]. Generally, sheet density or light scattering coefficient or even tensile strength is used to depict changes in interfibre bonding.

There are few alternatives to improve the internal bond strength of paper. Chemical treatment and beating are the most used alternatives. Extensive literature exists on the impact of these alternatives on the strength development of paper. Press-drying is among the alternatives that can improve the paper properties especially internal bond strength due to improved compressibility by the combined action of pressure and temperature [30, 33–37]. In press-drying paper is dried under restraint through the application of pressure in the z-direction during the drying process while the paper is simultaneously in contact with a very hot drying surface, thereby leading to a web temperature in excess of 100°C [30, 33–37]. The important feature of this process is the fact that it takes advantage of the positive effects of high web temperature on both dewatering rate by reducing the viscous resistance of water and web consolidation by increasing the compressibility of fibrous material [34].

Several reviews are available on the physics of press-drying [33–38]. The main factors that control the mechanical properties of press-dried paper and the performance of this process are the mechanical pressure applied on the wet web, the moisture content in the web, the pressing time and the temperature [30, 33–37]. In addition to the improvement in drying rate, this process leads to substantial energy savings and improvement in paper properties [33–38]. This process has been commercialised as Condebelt drying [33, 38]. Despite the proven advantages to the Condebelt drying process, this technology is still not widely accepted in the pulp and paper industry [33, 38]. There are only two installations of this technology worldwide [33]. At an industrial level, Retulainen et al. [39] reported that the Condebelt drying process led to substantial improvement in the paper properties and in the process efficiency as compared to the Cylinder drying process.

Despite the abundant literature on press-drying process and physics, only few studies have investigated the impact of process parameters on paper properties. Thus, laboratory pulp beating and paper press-drying experiments were conducted during this study on softwood and hardwood high-yield pulps so as to investigate the impact of this process while using large variations in fibre length, strength and interfibre bonding.

The main objective of this study was to discuss the impact of interfibre bonding development, intrinsic fibre strength and fibre length on the strength properties of press-dried paper. The specific objectives were: (1) to study the impact of pulp beating and press-drying temperature and pressure on paper internal bond strength; (2) to investigate the effect of IBS, intrinsic fibre strength and fibre length on paper strength development; and (3) to contribute to the fundamental understanding of strength development in press-dried paper.

2. Experimental procedures

Four high-yield pulps were used: one spruce TMP sampled after the first stage of refining from the Kruger, Trois-Rivières Mill (Quebec, Canada); three commercial bleached CTMPs obtained from the Tembec, Témisccamingue Mill, (Quebec, Canada) from birch, aspen and spruce. Pulps were beaten to various degrees in a PFI mill to ensure variation in fibre bonding (**Table 2**). The PFI mill was used to modify the cell wall structure and to minimise fibre fragmentation. Canadian standard freeness (CSF) was measured for each pulp. CTMP white spruce (*Picea glauca* (Moench) Voss samples were classified in a Bauer-McNett fibre classifier to investigate the impact of fibre length and distribution on strength development of paper. A total of nine pulps were obtained through the classification (**Table 2**) to ensure large variations in fibre length. The average fibre length of each class was measured by image analysis. The average weighted fibre length of each pulp was calculated on a dry weight basis (**Table 2**).

Series of 60 g/m^2 handsheets from each pulp were wet pressed and air-dried according to standard Tappi procedures and used as control samples. Other series were press dried at three different pressures (0.375; 0.750; 1.50 MPa) and temperatures (105; 140 and 175°C) using a hydraulic press with two heated platens. The moisture content (MC) of a sheet before press-drying is critical to the development of its strength [33–37]. In this study, handsheets had moisture contents (MC) ranging from 100–120% before press-drying. After press-drying, MC ranged from 6–9%. Paper properties were measured according to Tappi standard procedures. The internal bond strength was measured according to the method described in a previous report [25]. All samples were conditioned and tested at 20°C and 50% relative humidity (RH).

An analysis of variance was performed using the general linear model (GLM) SAS procedure [40] to test treatment effects. Regression and correlation analyses were performed with the CORR and REG SAS procedures. Results were considered significant at 95% and 99% probability levels.

Canadian standard freeness (CSF) (ml)	**Fibre classification in a Bauer McNett (%)**				**Average fibre Length (mm)**
	14	**28**	**48**	**<48**	
Unbleached Spruce TMP pulps (pulp sampled after the first stage of refining)					
475	22.4	34.5	12.8	31.3	1.43
295	13.7	28.9	20.4	37.0	1.40
220	12.5	28.5	20.5	37.5	1.35
130	12.8	27.5	20.2	39.5	1.32
Bleached Birch CTMP pulps (commercial pulp obtained from Tembec)					
420	0	9.9	50.5	39.6	1.03
340	0	19.0	39.7	41.1	1.02
250	0	18.2	36.8	44.6	0.96
200	0	15.5	36.5	48.0	0.92
Bleached Aspen CTMP pulps (commercial pulp obtained from Tembec)					
405	0	4.6	38.5	56.8	0.83
375	0	4.7	40.4	54.9	0.82
235	0	5.1	40.1	54.7	0.82
125	0	5.2	39.9	55.4	0.80
Bleached Spruce CTMP pulps (commercial pulp obtained from Tembec)					
750	100	0	0	0	2.85
750	0	100	0	0	2.03
750	0	0	100	0	1.34
750	40	40	20	0	2.07
540	32	32	16	20	1.88
540	24	24	12	40	1.78
480	16	16	8	60	1.22
450	8	8	4	80	0.98
480	0	0	0	100	0.66
540	28	31.5	15.7	24.8	1.75
485	29.8	27.7	15.9	26.6	1.74
400	29.8	27.2	16.9	26.1	1.74
350	29.7	27.5	13.5	29.1	1.70

Table 2. General characteristics of the studied pulps.

3. Results and discussion

3.1. Impact of pulp type, beating and press-drying on paper properties

Table 3 shows the results of the analysis of variance on the effect of pulp type, beating intensity and press-drying temperature and pressure on selected paper properties. All studied factors showed significant effects on paper properties, except for specific bond strength, where only pulp type had a significant effect.

The differences in the initial intrinsic characteristics of the studied pulps, including morphology, length distribution, intrinsic strength, specific area and chemical composition explain the significant effect of pulp type on paper properties. These differences are due to variations in wood species and pulping processes (**Table 2**). The first pulp is a commercial TMP spruce while the three other pulps are commercial CTMP pulps from birch, aspen and spruce. The chemical treatment softens the chips and results in longer, and more flexible pulps compared to the TMP pulp. The birch and the aspen CTMPs have shorter fibres than the spruce TMP and CTMP pulps. Compared to aspen, birch has higher wood density and higher cell thickness and fibre coarseness than aspen wood. All these differences along with the different fibre specific areas resulted in different paper properties (**Figures 2** and **3**).

The impact of beating on high-yield pulp properties is well-documented in the literature. Pulp beating modifies the fibre surface by generating fibrils, delamination and activation; improves the fibre specific area; slightly reduces the fibre length and produces fines [41, 42]. Data from **Table 2** show the changes in pulp properties. Fibre length shortened, and the proportion of fines increased, as the CSF decreased with beating intensity. All these changes improve the

Source of variation	DF	Paper properties					
		Density	ZSBK	IBS	SBS	BL	TI
Model	29	97.7^{**}	11.1^{**}	39.6^{**}	n.s.	11.2^{**}	9.5^{**}
Pulp	3	897^{**}	345^{**}	358^{**}	4.9^{*}	322^{**}	58.9^{**}
Beating	2	33.2^{**}	n.s.	24.7^{**}	n.s.	29.3^{**}	6.2^{*}
Temperature	2	17.8^{**}	n.s.	11.9^{**}	n.s.	14.1^{**}	31.2^{**}
Pressure	2	14.7^{**}	8.5^{*}	6.0^{*}	n.s.	4.0^{*}	7.6^{*}
R^2		0.98	0.94	0.94	0.28	0.94	0.77
CV, %		4.4	4.6	7.6	11.5	9.0	7.8

*Significant at $\alpha = 0.05$.

**Significant at $\alpha = 0.01$.

DF: Degree of freedom; ZSBL: Zero-span Breaking length; IBS: Internal bond strength; SBS: specific bond strength, BL: Breaking length; TI: Tear index; CV coefficient of variation; n.s. non-significant at $\alpha = 0.05$.

Table 3. Analysis of variance for the effect of beating and press-drying (temperature and pressure) on selected paper properties.

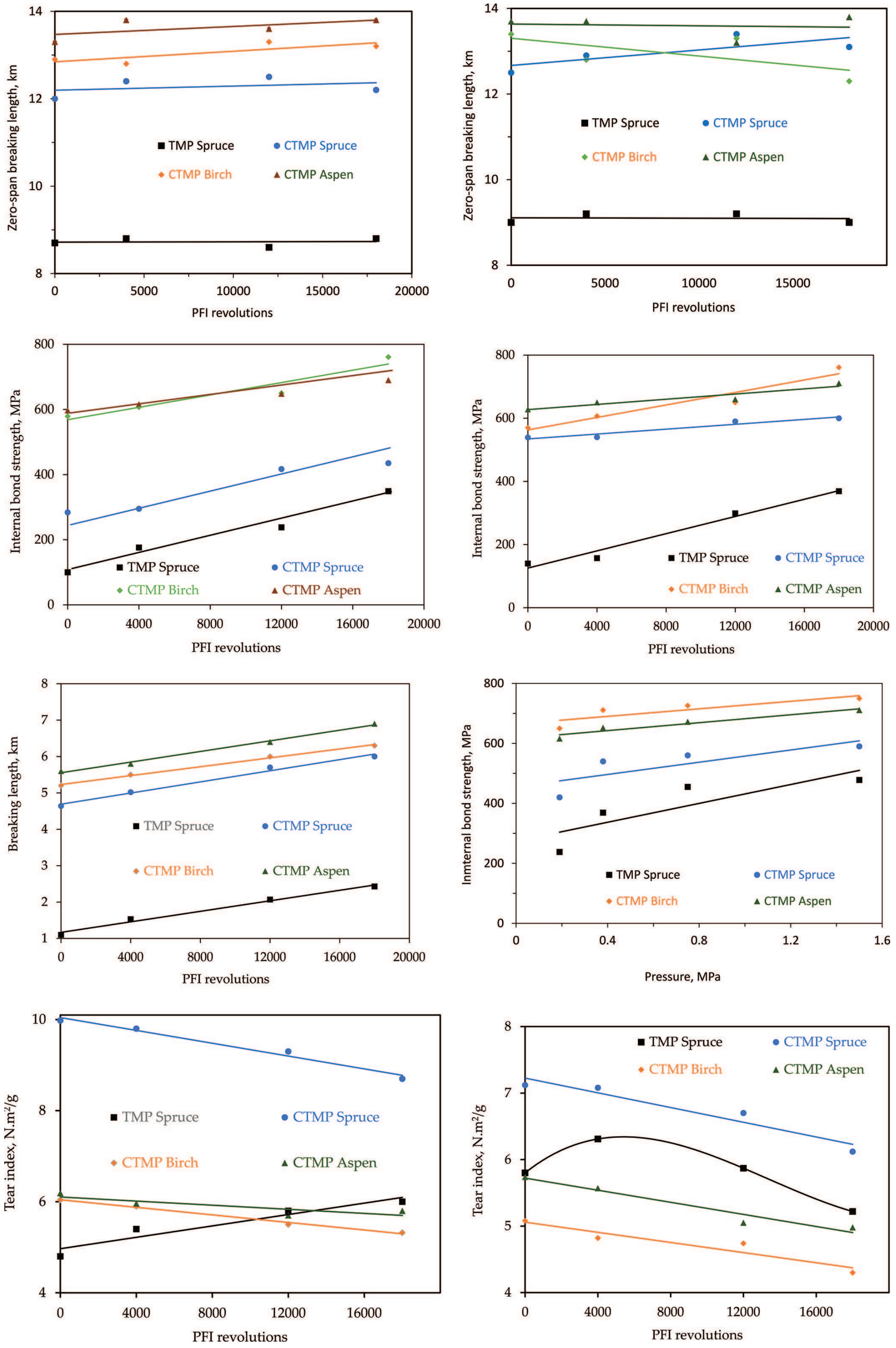


Figure 2. Effect of beating on selected properties of air-dried (left) and press-dried (right) paper made from high-yield pulps.

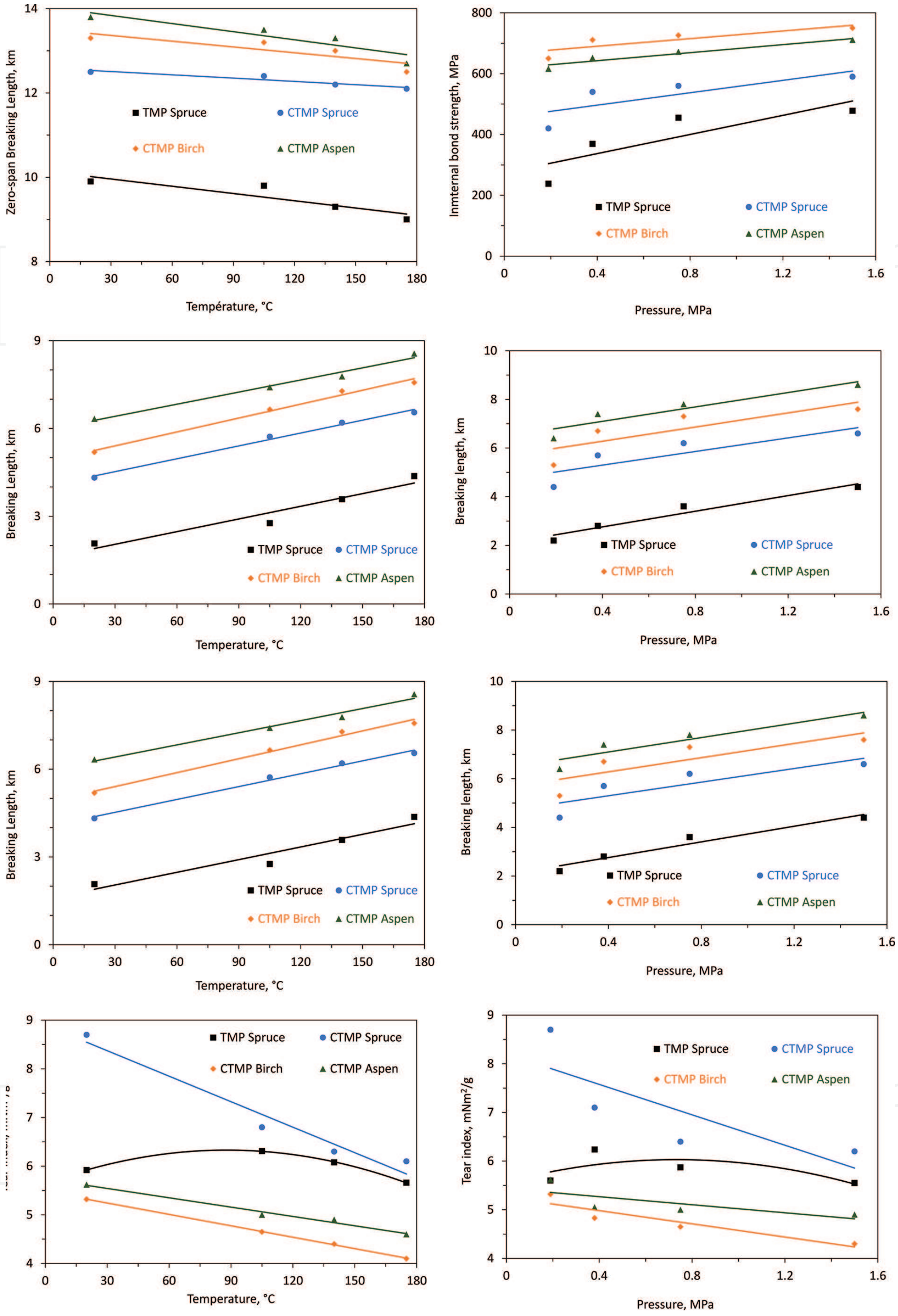


Figure 3. Effect of press-drying temperature (left) and pressure (right) on selected properties of papers made from high-yield pulps.

contact area between fibres, increase sheet density, lead to higher bonded areas and internal bond strength and consequently result in better tensile strength. **Figure 2** shows that beating improves the internal bond strength and the breaking length of both air-dried and press-dried paper from all high-yield pulps. However, beating decreases tear index, except for air-dried paper from the spruce TMP, where this property increased with beating (**Figure 2**). This increase results from an improvement in bonding. The press-dried TMP showed an initial increase after a slight beating and then decreased linearly outwards. This initial increase is also due to the improved bonding. The following decrease occurs because, at higher beating levels, the paper is well-bonded and the tear mechanism is then controlled by the fibre strength [6, 7].

Despite the observed tendency of a slight increase with beating, the effect of this treatment on the zero-span breaking length for the press-dried paper was not statistically significant. This result could be explained by the large variation in this property among the studied high-yield pulps. The variation in this property due to beating is marginal compared to that caused by pulp type (**Figure 2**). At all beating levels and pulp types, press-dried paper showed slightly higher zero-span breaking length than the air-dried paper. This result may be explained by the fact that the press-dried paper is denser than air-dried paper. In the testing zone, press-dried paper has a higher area occupied by the fibre wall and less void.

Press-drying temperature showed a significant effect on all paper properties except for specific bond strength and intrinsic fibre strength (**Table 3**). **Figure 3** shows the variation of selected properties with press-drying temperature and pressure. Higher temperatures soften the wood fibres and make them more compressible. Thus, paper density increases with increased PD temperature, which leads to a higher contact area, and therefore, to a higher bond strength. This result was expected, and is in good agreement with previous findings where close and positive relationships were reported between the bonded area, the internal bond strength and the tensile strength of paper [4, 6, 7, 25–27, 30, 31].

The effect of beating and press-drying temperature and pressure on the specific bond of paper was not statistically significant (**Table 2**). At the tested beating and press-drying parameters, little variation of the specific bond strength is observed for spruce TMP (1600–1800 MPa), spruce CTMP (1400–1700 MPa), birch CTMP (1700–1900) and aspen CTMP (1500–1800). This result suggests that the improvement in the internal bond strength is attributed to the increase in the bonded area and not to a change in the nature of the fibre-to-fibre bonds. These are thought to be mainly hydrogen bonds that break easily under the action of water [15, 30, 43]. Zerhouni et al. [32] also concluded that press-drying temperature did not change the nature of fibre-to-fibre bond in papers made from CTMP, TMP and kraft pulps and sludge. The specific bond strength did not vary with neither the press-drying temperature nor the paper composition.

The variation in press-drying temperature also affects the fibre chemical structure as demonstrated in a previous report [15]. In this study, the surface chemistry of air-dried and press-dried spruce and birch CTMP papers were analysed by electron surface chemical analysis (ESCA) and the oxygen to carbon ratios (O/C) were reported. A decrease in the O/C ratio indicates an increase in the lignin content at the fibre surface. Results from this investigation showed that, at 105°C, only water and volatile matter were evaporated and no chemical change occurred on the fibre surface as the O/C ratio remained constant at 0.53 (**Table 4**). At 140°C, hemicelluloses start to degrade, but lignin and cellulose are not affected. However, the ESCA results did not show any notable change in the fibre surface at this press-drying temperature since the O/C ratio also remained constant at 0.53. A PD temperature of 175°C

	Birch CTMP				Spruce CTMP			
	25°C	105°C	140°C	175°C	25°C	105°C	140 °C	175°C
Carbon concentration, %	64.5	65.0	65.2	67.0	65.1	64.8	64.7	64.8
Oxygen concentration, %	34.6	34.4	33.8	32.2	34.5	34.1	34.5	32.4
O/C ratio	0.54	0.53	0.52	0.48	0.53	0.53	0.53	0.48
Wet breaking length, m	65	77	82	110	64	100	120	192

Table 4. Effect of drying temperature on the concentrations of carbon and oxygen, O/C ratio and wet breaking length of press-dried birch and spruce CTMP [15].

showed significant chemical changes at the fibre surface as indicated by the O/C ratio which decreased from 0.53 to 0.48. At this temperature, lignin flows at the fibre surface and protects the formed hydrogen bonds from moisture [15].

The variation in the wet breaking length of press-dried papers with temperature supports this finding (**Table 4**). For example, for the press-dried spruce TMP at 175°C, the wet breaking length improved by 364, 151 and 73% compared to those dried at 25, 105 and 140 °C, respectively. This improvement in the wet breaking length for press-dried CTMPs at 175°C was less important than that for the TMP. For the aspen, birch and spruce CTMPs, the improvement from 25–175°C was 136, 131 and 63%, respectively. The fact that the CTMPs were bleached led to less lignin present on the fibre surface, and these fibres were more hydrophile than the TMP fibres.

The PD pressure had a significant effect on all paper properties except for specific bond strength. Increasing pressure increases the bonded area, which improves the probability of hydrogen bond formation and also improves the density of the paper. This led to improved bond strength and consequently to improved tensile properties. The increase in the internal bond strength caused by pressure also led to a decrease in the tear resistance, as previously explained. Surprisingly, the press-drying pressure showed a significant effect on the zero-span breaking length (**Table 3**). Increasing the pressure decreased this property (**Figure 3**). The compression effect on the fibre increases the area occupied by the fibre wall in the testing zone, which is expected to improve the zero-span. However, a slight decrease in this property is observed with increasing press-drying pressure (**Figure 3**). This decrease could be attributed to the mechanical damage of the fibre due to increased pressure [5].

3.2. Impact of fibre strength on the development of paper properties

Intrinsic fibre strength plays an important role in the development of different paper properties. Indeed, rupture during testing could occur in the fibre or in the bond between fibres. Several studies [5, 26, 41, 44–51] demonstrated that during rupture in tensile testing of paper, some fibres pull out and others break. Beating weakens the fibres and the proportion of broken fibres during paper testing increases with the beating level.

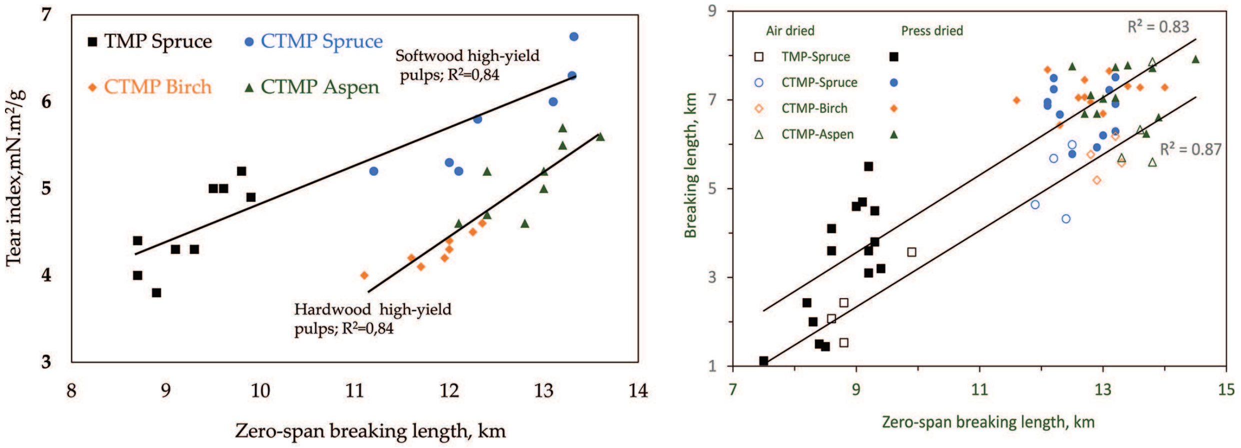
There was no clear relationship between the tear index and the zero-span breaking length of the pulps at any of the beating levels tested. This is not because fibre strength did not influence tear index, but because the effects of bonding and fibre length on tear index were more important and also because of the low range in fibre strength variation compared to those of internal bond strength and fibre length. Thus, the impact of fibre strength on the tear index could be hidden.

The relationship between zero-span breaking length and the tear index for beating levels where there was enough data with similar bond strength values was studied. Two distinct relationships were found at the same level of bonding, one for softwoods and one for hardwoods. These relationships were highly significant and explained more than 81% of the total variation in tear index (**Figure 4a**). This close relationship between the zero-span breaking length and tear index is in good agreement with previous findings [5–8, 51]. The difference between hardwood and softwood pulps is due to the impact of fibre length on the development of tear index.

For tensile strength, a linear relationship between breaking length and zero-breaking length was found for air-dried and press-dried paper (**Figure 4b**). This pattern of variation was expected, considering the variation in fibre strength among the TMP and CTMPs. Indeed, the TMP fibres showed lower fibre strength than the CTMP pulps at all beating levels and press-drying conditions. The press-dried paper tended to have slightly higher fibre strength and tensile properties compared to the air-dried paper. Better bonding can explain the higher tensile strength, while better fibre compressibility explains the better fibre strength of press-dried paper. The better fibre compressibility results in a higher area occupied by the fibre wall and lower void area in the test zone, which explains the higher zero-span breaking length of press-dried paper compared to air-dried paper.

Despite the high coefficients of determination ($R^2 > 0.85$), one can still observe a high scattering of the experimental data around the relationships for air-dried and press-dried papers. The variation in fibre morphology and bond strength, along with the experimental errors, explains this high scattering.

The close relationships between fibre strength and paper tensile and tear strengths are well documented in the literature [1–11, 26, 41, 44–51]. However, previous studies used chemical



(a) (b)

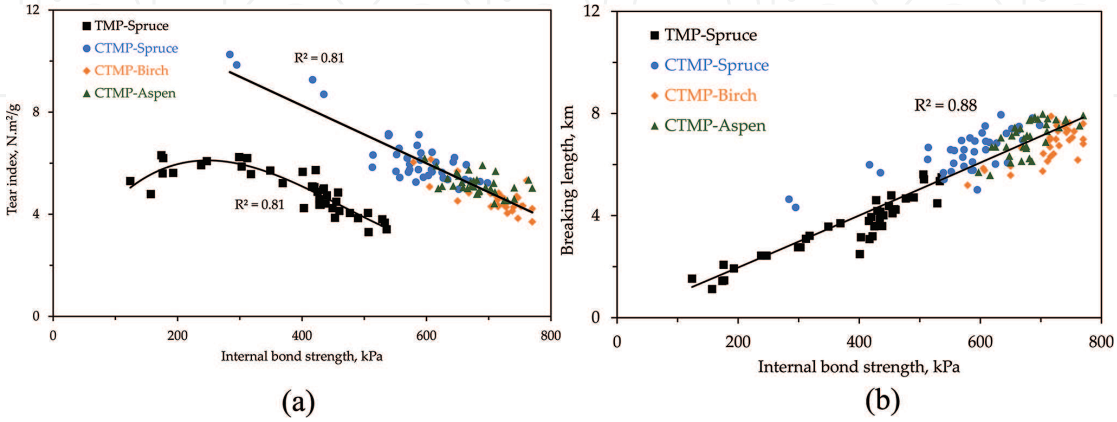
Figure 4. Effect of fibre strength on (a) the tear index and (b) the tensile breaking length of air-dried and press-dried papers made from high-yield pulps.

treatments or modification to vary the fibre strength to investigate this relationship [18–20, 49]. In addition, only a few studies investigated the impact of fibre strength on paper mechanical properties of high-yield pulps [12, 15, 28–30]. This study confirmed the importance of fibre strength in the development of tensile and tear strengths of high-yield pulps. Variations in pulp type, wood species and drying parameters along with refining led to an important variation in the fibre strength.

3.3. Impact of internal bond strength on paper properties

The observed variations in paper properties, namely the tear index (**Figure 5a**) and the breaking length (**Figure 5b**), are due to the effects of both beating and press-drying on internal bond strength. Data from the TMP and CTMP pulps followed two distinct relationships (**Figure 5a**). This result is due to several differences in the properties of TMP and CTMP pulps including fibre flexibility, compressibility and strength. Data from the present study show that the zero-span breaking length of the TMP ranged from 7.5 to 9.9 km while that of the CTMPs ranged from 11.7 to 14.7 (**Figures 2** and **3**). CTMP fibres are reported to be more flexible and more compressible than TMP fibres [29, 30]. The tensile modulus of elasticity of paper is closely related to fibre flexibility [9, 10, 30]. The tensile modulus of elasticity for the TMP papers ranged from 0.75 to 1.85 GPa while that of CTMP papers was much higher and ranged from 1.4 to 4.8 GPa [30]. Thus, CTMP fibres were more flexible than TMP fibres, thereby explaining the distinct relationships of TMP and CTMP paper (**Figure 5a**). As stated earlier, flexible fibres are more compressible and result in denser paper and in a higher area occupied by the fibre wall and a lower void area in the test zone.

For the TMP, the pattern of variation is typical of the tear index variation with interfibre bonding (**Figure 1**). The tear index initially increased with increasing bond strength to reach a maximum around 6 N·m^2/g, beyond which it started to decrease consistently with increasing bond strength (**Figure 5a**). The initial increase is due to the fact that below the maximum tear index the paper is weakly bonded. Thus, more fibres pull out than break in the tear zone and the tear index is controlled to a greater extent by the number of bonds that break than by the fibre breakage. Beyond the maximum tear index, where the level of bonding is high, more fibres break than pull out along the tear zone [3, 6–8].



(a) (b)

Figure 5. Effect of the internal bond strength on (a) the tear index and (b) tensile breaking length of press-dried and air-dried paper made from high-yield pulps.

In the case of CTMPs, the tear index of the pulps decreased consistently with increasing internal bond strength (**Figure 5a**). The three pulps tended to follow the same relationship. For each CTMP pulp, air-dried handsheets showed a higher tear index than press-dried ones (**Figures 2** and **3**). The experimental data of the internal bond strength and the tear index are scattered around both relationships (**Figure 5a**). This scattering is due to several factors including variations in fibre strength caused by beating and press-drying, to changes in fibre length due to species variation and to experimental error.

Fibre strength variation could also explain the differences between the tear index of various pulps. Despite its shorter fibre length, the aspen CTMP showed higher tear index values compared to the birch CTMP (**Figures 2** and **3**). The lower fibre coarseness and higher fibre strength of the aspen fibres compared to those of birch explain this result. The spruce CTMP showed the highest tear index because of its higher fibre length.

A close linear relationship was found between internal bond strength and tensile breaking length (**Figure 5b**). It is interesting to note that all the experimental data generated in the present study follow this relationship with a high coefficient of determination ($R^2 = 0.88$). This suggests that internal bond strength is the main controlling factor in the development of tensile strength of paper. This result is in good agreement with previous findings [4, 25, 41]. **Figure 5b** shows that the experimental data is scattered around the regression despite the high coefficient of determination. This scattering can be explained by the experimental error and the role of intrinsic fibre properties in the development of paper strength, namely fibre strength and fibre length.

3.4. Impact of fibre length and distribution on paper properties

Fibre length also plays an important role in the development of paper tearing resistance and tensile strength. The effect of fibre length is clearly seen in **Figure 4a** where the softwood pulps presented higher tear index values than the hardwood pulps at all constant fibre strengths. Similarly, the spruce CTMP showed a higher tear index than the birch and the aspen CTMPs (**Figure 4a**).

The tear index of both air-dried and press-dried paper was proportional to the fibre length of all classified spruce CTMP (**Figure 6a**). However, the tear index of press-dried handsheets was lower than that of air-dried ones. This result also shows that increasing bonding through press-drying decreases the tear index. The slope of the tear index variation with fibre length was also lower for the press-dried paper compared to air-dried paper. Thus, the dependence of tear index on fibre length was less important for press-dried paper. These results agree with Seth and Page [7] and can be explained by the tear mechanism as discussed in the previous sections. In the air-dried handsheets, the fibres were weakly bonded (internal bond strength varied from 80 to 290 kPa). Thus, tear index is controlled to a greater extent by the number of bonds that break along the length of the fibres. However, in press-dried handsheets, interfibre bonding was high (internal bond strength varied from 480 to 610 kPa), and consequently, the tear index is controlled to a greater extent by fibre breakage than by bond breakage.

Fibre length distribution also showed an important impact on the tear index (**Figure 6b**). An increasing proportion of fines led to a linear decrease in the tear index. In fact, higher proportions

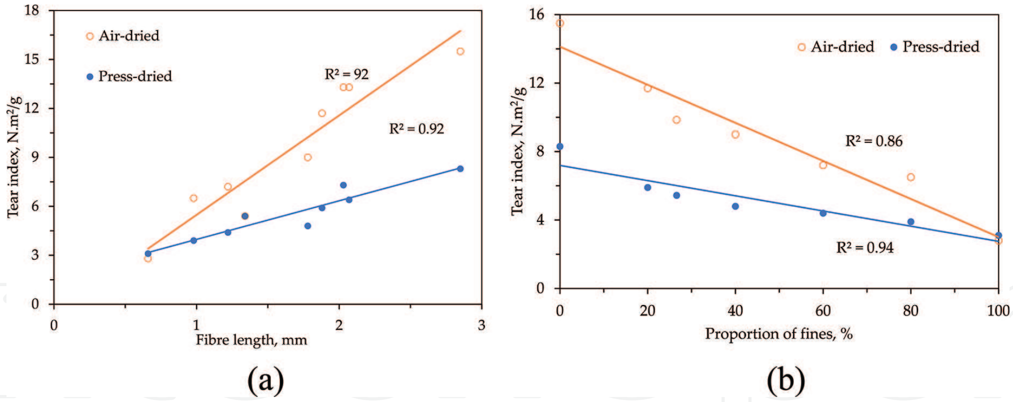


Figure 6. Effect of (a) fibre length and (b) distribution on the tear index of air-dried and press-dried paper at 175°C and 0.75 MPa made from white spruce classified CTMP pulps.

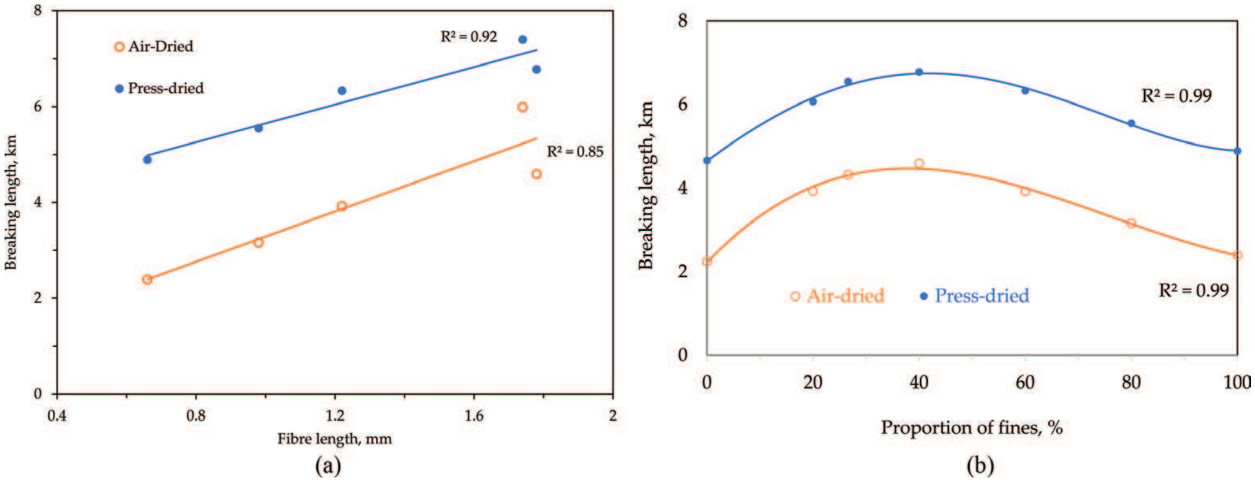


Figure 7. Effect of (a) fibre length (comparable CFS at 450 ± 30 ml) and (b) fibre distribution on the tensile breaking length of air-dried and press-dried paper at 175°C and 0.75 MPa made from white spruce classified CTMP.

of fines improved bonding and reduced the average fibre length in the paper. Both changes are known to decrease the tear index.

Figure 7a and **b** shows the impact of fibre length and distribution, respectively, on paper tensile strength. At comparable CSFs (450 ± 30 ml), an increasing fibre length led to a linear increase in the tensile breaking length. The latter is also controlled by the fibre distribution. The optimum breaking length occurred at around 40% of fines. The initial improvement in the tensile strength from 0% to about 40% is due to the improvement in fibre contact area. Beyond a 60% proportion of fines, the tensile strength showed a linear decrease due to the reduction in the proportion of long fibres. Long fibres lead to better stress distribution along the fibre network while fines lead to stress concentration in the fibre network [52], which explains the decrease in tensile strength when fines content is above 60%. The decrease in the tensile strength with high fines content is in a good agreement with previous findings [3, 11, 12, 41, 53].

4. Conclusion

The properties of high-yield pulps can be improved by beating and paper press-drying. Pulp refining changes the fibre surface morphology, promoting mechanical adhesion between fibres. Compared to air-dried paper, PD paper showed much higher internal bond strength, breaking length and wet breaking length for all tested pulps and at all refining levels. These results are due to the increase in the bonded areas. PD temperature softens the fibres and changes their surface chemistry, while PD pressure improves the contact area between fibres. These changes led to an important improvement in internal bond strength, which explained to a large extent the variations in the tensile strength properties of paper. Two opposite tendencies were observed for the tear index. In the well-bonded paper, press-drying leads to a lower tear index compared to air-drying, while in the weakly bonded paper, press-drying leads to a higher tear index compared to air-drying.

Fibre length and intrinsic strength also played important roles in the strength development of paper. However, their impact was less important for the press-dried paper as compared to the air-dried paper.

List of abbreviations

AD	air drying
BL	breaking length
CSF	Canadian standard freeness
CTMP	chemi-thermomechanical pulp
CV	coefficient of variation
DF	degree of freedom
ESCA	electron surface chemical analysis
IBS	internal bond strength
MC	moisture content
O/C	oxygen to carbon ratio
PD	press drying
RH	relative humidity
SBS	specific bond strength
TI	tear index
TMP	thermomechanical pulp
ZSBL	zero-span breaking length

Author details

Ahmed Koubaa[1]* and Zoltan Koran[2]

*Address all correspondence to: ahmed.koubaa@uqat.ca

1 Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, Canada

2 Université du Québec à Trois-Rivières, Trois-Rivières, Canada

References

[1] Page DH. A theory for the tensile strength of paper. Tappi. 1969;**52**(4):674-681

[2] Page DH, MacLeod JM. Fiber strength and its impact on tear strength. Tappi. 1992;**75**(7):122-125

[3] Clark J'A. Components of the strength qualities of pulps. Tappi. 1973;**56**(7):122-125

[4] Andersson M, Mohlin U-B. Z-strength of mechanical pulps. Paperi Puu. 1980;**62**(10):583-586

[5] Wathén R. Studies on fiber strength and its effect on paper properties. [thesis]. Department of Forest Products Technology, Helsinki University of Technology; 2006

[6] Page DH. A note on the mechanism of tearing strength. Tappi. 1994;**77**(3):201-203

[7] Seth RS, Page DH. Fibre properties and tearing resistance. Tappi. 1988;**71**(2):103-107

[8] Kärenlampi PP. The effect of fibre properties on the tearing work of paper. Tappi. 1996;**79**(4):211-216

[9] Page DH, Seth RS, De Grace JH. The elastic modulus of paper. I. The controlling mechanisms. Tappi. 1979;**62**(9):99-102

[10] Cowan WF. Explaining handsheet tensile and tear in terms of fiber-quality numbers. Tappi. 1995;**46**(3):101-106

[11] Paavilainen L. Influence of fiber morphology and processing on the softwood sulphate pulp fibre and paper properties [thesis]. Helsinki: Helsinki University of technology; 1993

[12] Retulainen E, Luukko K, Fagerholm K, Pere J, Laine J, Paulapuro H. Papermaking quality of fines from different pulps – The effect of size, shape and chemical composition. Appita Journal. 2002;**55**:457-460

[13] Seth RS, Bennington CPJ. Fiber morphology and the response of pulps to medium-consistency fluidization. Tappi Journal. 1995;**78**(12):152-154

[14] Sundblad S. Predictions of pulp and paper properties based on fiber morphology [thesis]. Stockholm, Sweeden: KCH; 2015

[15] Koubaa A, Riedl B, Koran Z. Surface analysis of press dried-CTMP paper samples by electron spectroscopy for chemical analysis. Journal of Applied Polymer Science. 1996;**61**(3):545-552

[16] Oksanen T, Buchert J, Viikari L. The role of hemiocelluloses in the hornification of bleached Kraft pulps. Holzforschung. 1997;**51**(4):355-360

[17] Schönberg C, Oksanen T, Suurnäkki A, Kettunen H, Buchert J. The importance of xylan for the strength properties of spruce Kraft pulp fibres. Holzforschung. 2001;**55**(6):639-644

[18] Sjöberg J, Kleen M, Dahlman O, Agnemo R, Sundvall H. Fiber surface composition and its relations to papermaking properties of soda- anthraquinone and Kraft pulps. Nordic Pulp and Paper Research Journal. 2004;**19**(3):392-396

[19] Spiegelberg HL. The effect of hemicelluloses on the mechanical properties of individual pulp fibers. Tappi. 1966;**49**(9):388-396

[20] Treimanis A. Wood pulp fiber structure and chemical composition, their influence on technological processes. Nordic Pulp and Paper Research Journal. 1996;**11**(3):146-151

[21] Duchesne I, Hult E-L, Mohlin U, Daniel G, Iversen T, Lennholm H. The influence of hemicellulose on fibril aggregation of Kraft pulp fibres as revealed by FE-SEM and CP/MAS13C-NMR. Cellulose. 2001;**8**(2):103-111

[22] Lindström T. Chemical factors affecting the behaviour of fibres during papermaking. Nordic Pulp and Paper Research Journal. 1992;**7**(4):181-192

[23] Seth RS, Chan BK. Measuring fiber strength of papermaking pulps. Tappi. 1999;**82**(11):115-120

[24] Seth RS. Zero-span tensile strength of papermaking fibers. Paperi ja Puu – Paper and timber. Tappi. 2001;**83**(8):597-604

[25] Koubaa A, Koran Z. Measure of the internal bond strength of paper/board. Tappi. 1995;**78**(3):103-111

[26] Niskanen KJ, Alava MJ, Seppälä ET, Åström J. Fracture energy in fibre and bond failure. Journal of Pulp and Paper Science. 1999;**25**(5):167-169

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

[28] Broderick G, Paris J, Valade JL, Wood J. Linking the fibre characteristics and handsheet properties of a high-yield pulp. Tappi. 1996;**79**(1):161-169

[29] Walker JCF. Pulp and paper manufacture. In: Primary Wood Processing: Principles and Practice. Dordrecht, The Netherlands: Springer; 2006. pp. 477-534

[30] Koubaa A. Amélioration de la résistance des liaisons dans le papier et le carton par raffinage et par pressage et séchage simultanés [thesis]. Université du Québec à Trois-Rivières

[31] Andersson M. Z-strength in pulp characterization – Chemical pulps. Svensk Papperstidning. 1981;**84**(3):R6-R14

[32] Zerhouni A, Mahmood T, Koubaa A. The use of paper mill biotreatment residue as furnish or as a bonding agent in the manufacture of fibre-based boards. J-For. 2012;**2**(2):19-24

[33] Lobosco V, Kaul V. An elastic/viscoplastic model of the fibre network stress in wet pressing. Part 2: Accounting for pulp properties and web temperature. Nordic Pulp and Paper Research Journal. 2001;**16**(4):313-318

[34] Lucisano MFC. On heat and paper: From hot pressing to impulse technology [thesis]. Stockholm: Royal Institute of Technology; 2002

[35] Andersson L, Back EL. The effect of temperature up to 90 C on dewatering of wet paper webs, evaluated in a press simulator. In: Proceedings of the TAPPI Engineering Conference. Atlanta, CA: TAPPI Press; 1981. pp. 311-323

[36] Back EL. A review of press drying. Technical Report D-224. STFI, Stockholm; 1984

[37] Back EL, Swenson R. The present state of press-drying of paper. In: The Role of Fundamental Research in Papermaking. Vol. Vol. 1. Cambridge: Mechanical Engineering Publishing Ltd; 1981. pp. 343-384

[38] Ghosh AK. Fundamentals of Paper Drying. In: Amimul Ahsan, editor Theory and Application from Industrial Perspective, Evaporation, Condensation and Heat transfer. InTech; 2011. pp. 535-582. ISBN: 978-953-307-583-9. Available from: http://www.intechopen.com/books/evaporation-condensation-and-heat-transfer/fundamentalsof-paper-drying-theory-and-application-from-industrial-perspective

[39] Retulainen E, Hämäläinen A. Three years of Condebelt drying at Stora Enso Pankakoski Mill in Finland. 1999 Tappi Engineering, Process & Product Quality Conference; 12-16 September 1999; Anaheim

[40] SAS Institute Inc. SAS Users Guide: Statistics. Version 6.03 edition. Cary: SAS Institute Inc; 1988

[41] Karlsson H. some aspects on strength properties in paper composed of different pulps [thesis]. Karlstad: Karlstad University; 2007

[42] Gharehkhani S, Sadeghinezhad E, Kazi SN, Yarmand H, Badarudin A, Safaei MR, Zubir MN. Basic effects of pulp refining on fiber properties—A review. Carbohydrate Polymers. 2015;**115**:785-803. DOI: 10.1016/j.carbpol.2014.08.047

[43] Przybysz P, Dubowik M, Kucner MA, Przybysz K, Przybysz Buzała K. Contribution of hydrogen bonds to paper strength properties. PLoS One. 2016;**11**(5):e0155809. DOI: 10.1371/journal.pone.0155809

[44] Van Den Akker JA, Lathrop AL, Voelker MH, Dearth LR. Importance of fiber strength to sheet strength. Tappi. 1958;**41**(8):416-425

[45] Buchanan JG, Washburn OV. The surface fractures of groundwood handsheets as observed with the scanning electron microscope. Pulp and Paper Magazine Canada. 1964;**65**(2):T52-T62

[46] Bronkhorst CA, Bennett KA. Chapter 7. Deformation and failure behavior of paper. In: Mark RE, Habeger Jr CC, Borch J, Lyne MB, editors. Handbook of Physical Testing of Paper. Vol. 1. 2nd ed. Revised and expanded. New York, Basel: Marcel Dekker Inc.; 2002. pp. 313-428

[47] Davidson RW. The weak link in paper dry strength. Tappi. 1972;**55**(4):567-573

[48] Kettunen H. Microscopic fracture in paper [thesis]. Espoo: Helsinki University of Technology; 2000

[49] Kärenlampi PYY. Fiber properties and paper fracture: Fiber length and fiber strength. In: Baker CF, editor. Transactions of the 11th Fundamental Research Symposium. The Fundamentals of Papermaking Materials. Vol. 1. Cambridge. UK: Pira International, September 21-26, 1997. pp. 521-545

[50] Yan N, Kortschot MT. Single fibre pull-out tests and the Elmendorf tear strength of paper. In: Proceedings 83rd Annual Meeting, Montreal. CPPA, Technical Section Preprints A. January 28-29, 1997; pp. A179-A183

[51] Lin B, He B, Liu Y, Ma L. Correlation analysis for Fiber characteristics and strength properties of softwood Kraft pulps from different stages of a bleaching fiber line. BioResources. 2014;**9**(3):5023-5033

[52] Migneault S, Koubaa A, Erchiqui F, Chaala A, Englund K, Wolcott MP. Application of micromechanical models to tensile properties of wood–plastic composites. Wood Science and Technology; 2011;**45**:521-532

[53] Fischer WJ, Mayr M, Spirk S, Reishofer D, Jagiello LA, Romana S, Colson J, Zankel A, Bauer W. Pulp fines—Characterization, sheet formation, and comparison to microfibrillated cellulose. Polymer. 2017;**9**:366-378. DOI: 10.3390/polym9080366