Factors affecting the free shrinkage of handsheets: apparent density, fines content, water retention value, and grammage

NADER MAYELI

ABSTRACT: Industrial papermaking is a high-speed process during which a suspension of cellulosic fibers is formed into a continuous web via dewatering followed by drying. Dewatering in the paper machine occurs mechanically in the forming and pressing sections; however, most of the remaining water, whose removal requires applying high temperatures, evaporates in the dryer section. As a result, the paper web shrinks, due to the shrinkage of individual fibers in the paper web. On the paper machine, the paper web is under restraint in the machine direction (MD), whereas it can shrink in the cross-machine direction (CD). The edges of the web shrink more than the center of the web. A shrinkage profile is therefore created in the CD of the web. All machine-made papers exhibit a CD shrinkage profile. The CD shrinkage profile is significant because it affects the final product quality and manufacturing efficiency. The prime cause of the CD shrinkage profile during drying is free shrinkage. The effects of several wood pulp fibers on the free shrinkage of handsheets were investigated to obtain deeper understanding of the mechanism of paper shrinkage during drying processes.

Application: Mills can better understand the role of different fiber types, density, fines content, water retention value, and grammage on the free shrinkage of handsheets formed from a selection of softwood and hardwood pulps.

After initial stock preparation processes, papermaking is essentially a process of water removal. In the first stage of manufacture, fibers are deposited as a dilute suspension via a filtration process to form a mat with solids content around 20%. In the second stage, the wet web is pressed, increasing the solids content between 40% and 50% and consolidating the web, which increases the amount of interfiber contact [1]. In what is typically the final stage, the web is dried, such that the equilibrium moisture content is around 8% [2,3]. During this drying process, the web shrinks [4] and this shrinkage affects the mechanical and printing properties of the sheet [5-7], which are specified by customers. Paper sheet shrinkage is not the direct consequence of water evaporation. However, it is a result of structural modification of individual fibers during drying, in particular by considerable transverse shrinkage that causes contraction of the fiber network and creates internal stresses in the paper. Cross-machine direction (CD) shrinkage exhibits a profile that it is greater at the edges of the web and minimal at the center, where the web is much more restrained compared with the edges [8-10]. A nonuniform mechanical property profile in the CD is a consequence of the shrinkage profile [7,11]. Drying tension builds up in the paper when paper is restrained from shrinking by the application of drying restraints. This drying tension is larger in the machine direction (MD) than in the CD because more fibers are oriented in the MD and fibers have higher longitudinal stiffness than transverse ones.

Several studies [11-13] have shown that the use of drying restraint for the purpose of reducing shrinkage affects the development of the paper sheet's mechanical properties. Increase in modulus of elasticity, decrease in stretch, and increase in tensile strength can be achieved by increasing drying restraint [12]. Wahlström [13] reported that an 8% strain increase, from -4% (shrinkage) to +4% (stretch), can give a relative increase in tensile stiffness of as much as 500%. It is now established that the shape of the shrinkage profile depends on length and width of the free draws in the dryer section [7,14]. The total amount of free shrinkage depends on the unrestrained shrinkage of the web in the CD and MD. Wahlström and Lif [7] showed that the geometric mean shrinkage was equal to the free shrinkage of an isotropic handsheet.

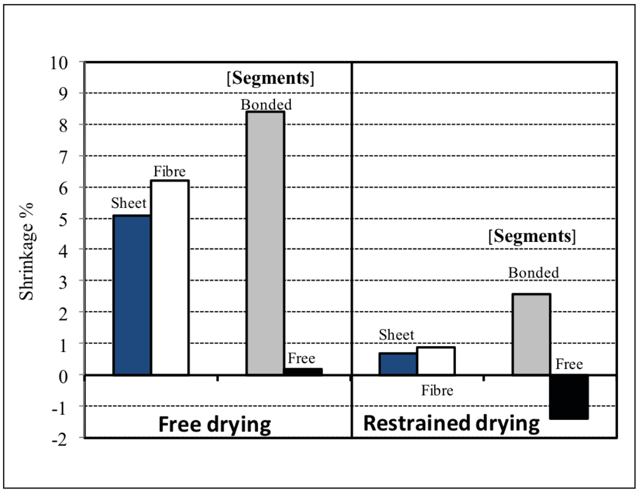
SHRINKAGE EVENT

As water is removed during drying, the attractive forces associated with the surface tension of water pull fibers sufficiently close so that hydrogen bonds can form between the fibers [15,16]. If the web is not restrained, these forces cause contraction of the web during drying. This shrinkage is the prime cause of deformations in the plane of paper at this stage. If the web is restrained during drying to prevent or reduce shrinkage, dried-in stresses are developed in the web [17,18]. Htun and de Ruvo [17] showed that the drying stress of restrained paper increases drastically after the solids content of the sheet reaches 80%, which was later proved by Nanko et al. [19]. Htun and de Ruvo concluded that the type of pulp and the degree of beating usually determine the starting point of the drying stress built up in the paper. They discussed that as solids content increases surface tension, drying forces and free shrinkage also increase [17]. In agreement with Htun and de Ruvo, Hansson et al. [20] stated that the greater part of the shrinkage happens in the solids content range of 60% to 80%. The magnitude of the shrinkage depends on the degree of swelling of the fibers and on the fiber orientation in the paper. Nanko et al. reported that the solids content from which this shrinkage starts is the fiber collapse point (FCP) and it is in the range of 85%–88% [19]. Fiber collapse point is the point at which the solids content is such that fibers are transformed from cylindrical tubes into flat ribbons to allow extended bonding area. At the FCP, the fibers shrink rapidly in the transverse direction, introducing microcompressions in the crossing fibers. Nanko et al. argued that the water remaining in the fiber wall at the FCP coincided with the value of bound water and stated that the evaporation of bound water, which has strong interaction with cellulose, caused the shrinkage of the fiber [19]. Later, Hoole et al. [10] proved that the profile is not caused by the press section and showed that shrinkage profile is set by the FCP.

FREE SHRINKAGE

Drying a paper without applying any external forces results in paper exhibiting shrinkage due to the hygroscopic nature of its constituent fibers as its moisture content reduces. It is accepted that fibers shrink by only 1%–2% along their length and by around 35% in width [20]. Shrinking of a single fiber in the direction of fiber width depends on the swelling capability of wood fiber components [21-23]. Accordingly, the classical interpretation of the mechanism of sheet shrinkage is that transverse shrinkage of fibers results in longitudinal contraction of contacting fibers in bonded regions [20,24]. Nanko and Wu [24] reported that the longitudinal shrinkage of the fibers is 30%–80% greater than that of the sheet, depending on the degree of beating. This finding was contrary to the results reported by Page and Tydeman [20], who found that the longitudinal shortening of the fibers was the same as the shrinkage of the sheet. What Nanko and Wu reported as the longitudinal shrinkage of the fibers is more likely to be the longitudinal contraction of crossing fibers at the bond, because they measured the shrinkage of the fibers in the sheet. According to Nanko and Wu, the longitudinal shrinkage of the fibers often happens at the bonded area in the freely dried sheet, which had been proved by Page and Tydeman.

Figure 1 shows the average longitudinal shrinkage of a sheet, an individual fiber in the sheet, and the segments (bonding sites and free segments) of a fiber in a fiber network [24]. In a freely dried sheet, the bonded segments shrink more than the bonded segments in the restrained dried sheet case. The shrinkage rate of the bonded segments is larger than that of fiber. Nanko and Wu observed no significant dimensional change in free segments of freely dried paper and found that the free shrinkage of the sheet was somewhat less than the longitudinal contraction of fibers. They noticed that during restrained drying, contraction of bonded segments causes stretching of free segments that are situated between two bonded segments (Fig. 1). As mentioned earlier, water elimination from a swollen fiber during drying results in considerable fiber shrinkage; that is, as water is removed from the cell wall, the fiber begins to decrease in cross-section as surface tension forces draw the fibrous components together [16,23,25]. Hansson et al. [21] reported that if no external forces are applied on paper during drying, the magnitude of the free shrinkage depends on the degree of fiber swelling in the paper.



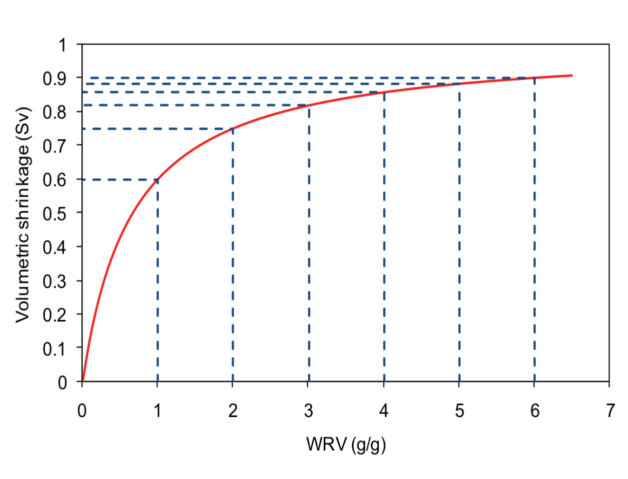
1. Average fiber shrinkage during free and restrained drying.

Sampson and Yamamoto [26] investigated the influence of water retention value (WRV) on the free shrinkage of handsheets. Assuming the density of the fiber wall to be 1.5 g/cm^3, a simple mass balance can be used to show that the total volumetric shrinkage of a fiber on complete drying from a moisture content, m, is (Eq. 1) [26]:

$$S_v \approx \frac{3m}{3m+2} \qquad (1)$$

This volumetric shrinkage of fibers provides the driving force for the shrinkage of paper (**Fig. 2**). Sampso and Yamamoto reported that although free shrinkage was directly proportional to WRV, an analysis based on volumetric shrinkage of fiber, S_v, revealed that this dependence is not influenced significantly by WRV, which is greater for fines than it is for fibers (WRV substitutes for parameter m in [Eq. 1]).

Several studies have shown that fines have a strong influence on the structure and properties of the fiber network [15,25,27-30]. The primary effect of fines is an increase in



2. Volumetric shrinkage plotted against water retention value (WRV).

Fiber Type	Pulp Type	SR Value (No Beating)
Softwoods		
BP	Bleached Lapponia pine*	7
BS1	Bleached Mercer spruce**	8
BS2	Bleached star spruce***	14
UBSP	Unbleached spruce/pine (70:30 blend)*	9
Hardwoods		
BB1	Bleached Eno birch*	10
BB2	Bleached Södra gold birch*	13
BE	Bleached eucalyptus*	11
Notes: *Kraft; **sulfite; ***chemithermomechanical.		

I. Pulping procedures.

density, which results in an increased number of interfiber bonds and improved tensile-strength properties of the sheet [25,27-29]. Fines act as a bridge between fibers, contributing to the formation of a coherent paper network. Uesaka and Moss [29] showed that the fines considerably increase shrinkage; in particular the chemical pulp (low-yield sulfite) fines gave a greater increase than the mechanical pulp (groundwood) fines. Sampson and Yamamoto showed that the free shrinkage of handsheets is strongly influenced by the fraction of fines retained in the sheet. They stated that in the absence of fines, the increased density due to beating has only a small influence on free shrinkage. They also provided experimental evidence confirming that the shrinkage should increase with sheet grammage [26]. The proposed mechanism for this grammage dependance is that fibers located at the sheet surfaces are less efficient at transferring shrinkage forces to other fibers because they can induce longitudinal contraction with other fibers on one side only, and the fraction of all fibers that are located in the surfaces of the sheet diminishes with increasing grammage. They reported that when fines were removed from the sheet, no grammage dependence of free shrinkage was observed.

The purpose of this paper is to better understand the mechanism of free shrinkage during drying by investigating the influence of several softwood (SW) and hardwood (HW) pulp fibers on the free shrinkage of handsheets and the factors that can affect it.

EXPERIMENTAL

Seven commercial once-dried pulps were investigated in this study (**Table I**). Pulps were soaked for 24 h and beaten in a Valley beater according to TAPPI T-200 “Laboratory beating of pulp (Valley beater method)”; samples were taken at regular intervals. Schopper Riegler (SR) freeness of all pulp samples was measured according to TAPPI T-227 “Freeness of pulp (Canadian standard method)”. Measurements of fiber geometry of the pulps are summarized in **Table II**. The fines content was obtained using a Somerville fractionator fitted with

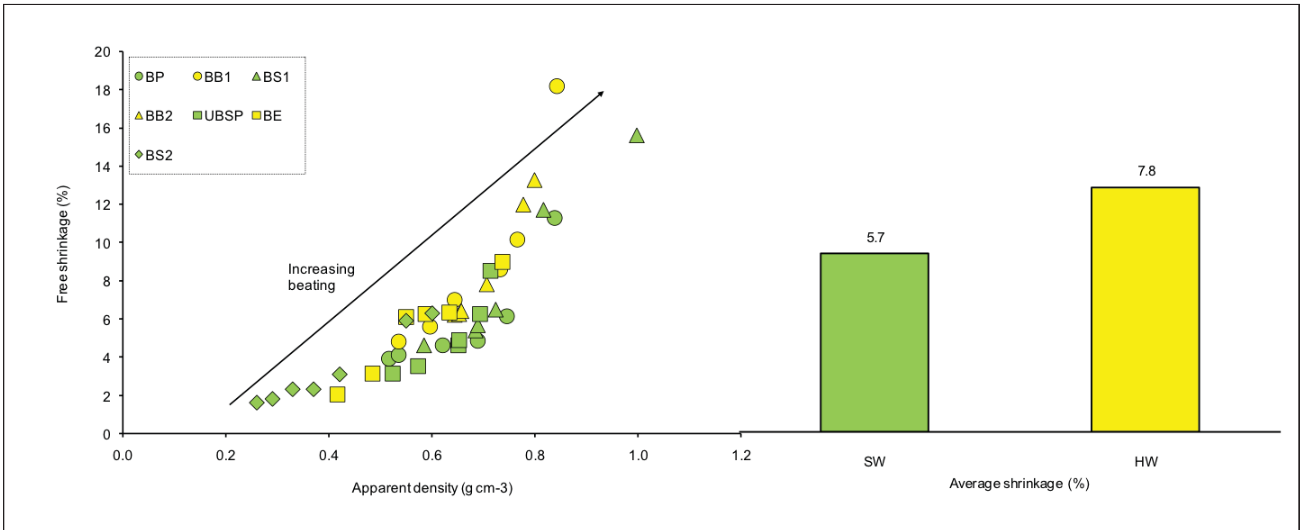
Pulp Samples	Mean Length, mm	Standard Deviation (δ)	Coefficient of Variation (CV)	Mean Width, µm	Standard Deviation (δ)	Coefficient of Variation (CV)	Mean Wall Thickness, µm	Standard Deviation (δ)	Coefficient of Variation (CV)
BP	3.79	0.39	0.10	32.90	6.00	0.18	6.81	0.96	0.14
BS1	4.13	0.59	0.14	32.30	6.76	0.21	4.17	0.54	0.13
BS2	3.63	0.45	0.12	35.70	4.58	0.13	4.46	0.76	0.17
UBSP	4.36	0.57	0.13	47.50	5.55	0.12	8.03	0.30	0.04
BB1	1.02	0.18	0.18	16.20	4.38	0.27	2.19	0.46	0.21
BB2	1.04	0.17	0.17	13.11	2.89	0.22	3.13	0.50	0.16
BE	1.37	0.30	0.22	20.90	3.87	0.19	6.27	0.38	0.06

II. Pulp fiber geometry measurements.

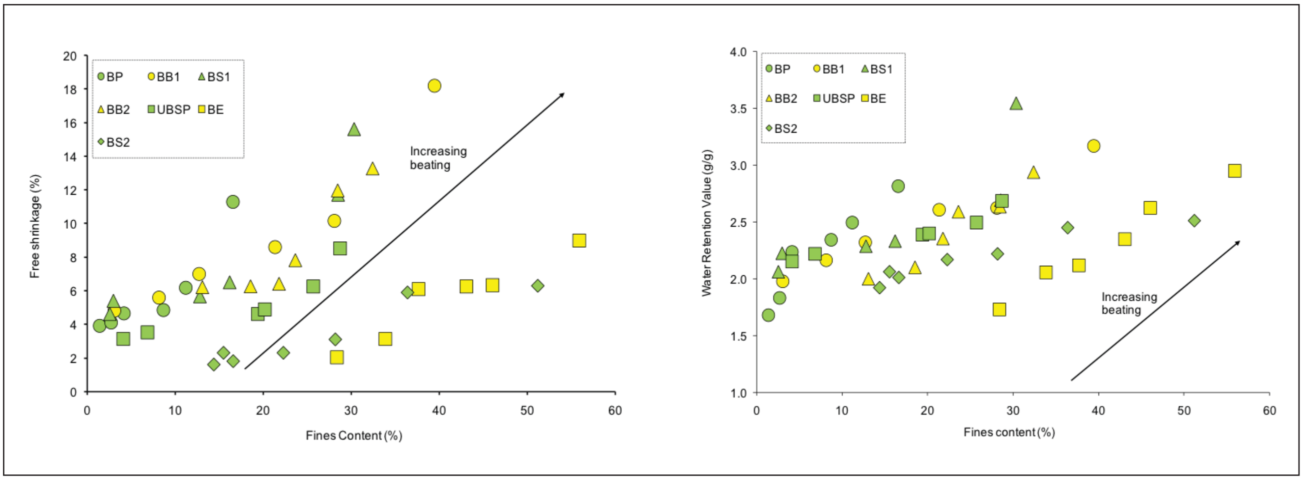
200 mesh screen according to TAPPI UM 242 "Shive content of mechanical pulp (Somerville fractionator)". The WRV of the pulps was determined by centrifugation. Sets of standard handsheets (60 g/m²) were made from the whole pulp samples in a standard handsheet former and press according to TAPPI T-205 "Forming handsheets for physical tests of pulp". They were then dried and conditioned under controlled temperature and humidity 23 ± 1°C and 50% ± 2% RH for a minimum of 24 h before testing for grammage and thickness. To investigate the influence of grammage on free shrinkage, handsheets were formed with grammage between 20 and 120 g/m² for each pulp for three beating times. Their free shrinkage was determined by measuring the distance after free drying between a pair of marks made on a wet sheet after pressing according to TAPPI T-205. For the sheets formed with a range of grammages, the intrinsic density was computed from the gradient of a plot of grammage against thickness. In all cases a linear regression on the data exhibited a coefficient of determination greater than 0.96, confirming that there was no significant effect of grammage on the density of sheets, and hence on the extent of contact between fibers.

RESULTS AND DISCUSSION

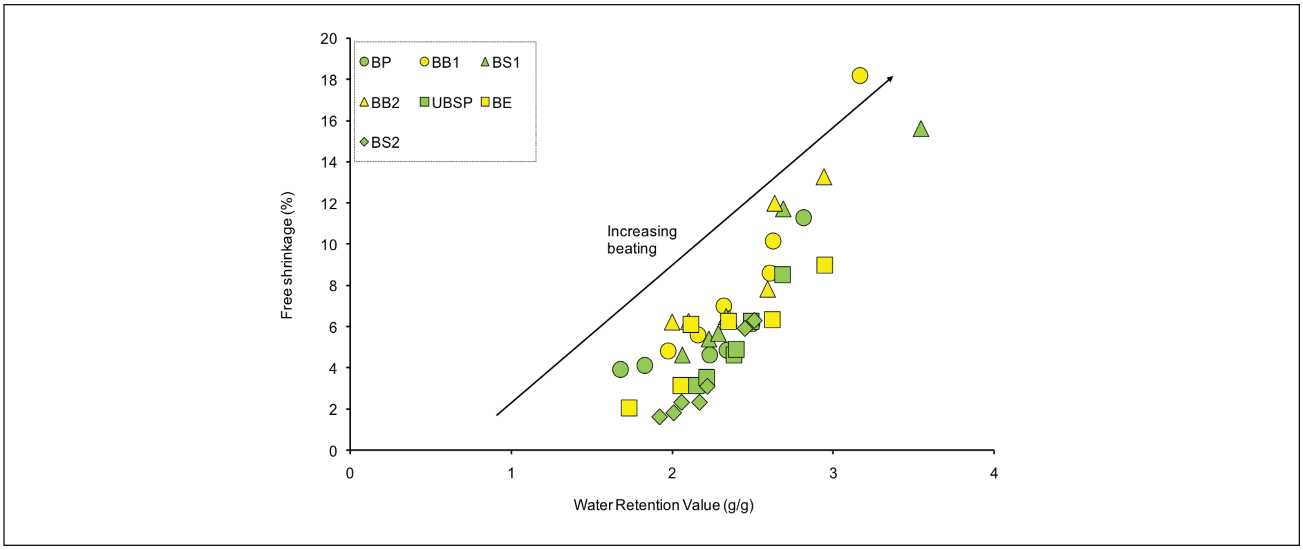
The free shrinkage of 60 g/m² handsheets is plotted against apparent density in **Fig. 3**. As anticipated, the free shrinkage increases with apparent density for all pulps. The free shrinkage of Mercer spruce, eucalyptus, and star spruce pulps increases linearly with density, which yields a coefficient of determination greater than 0.942, while the free shrinkage of Lapponia pine, Eno birch, Södra gold birch, and spruce/pine blend pulps increases exponentially with density, which yields a coefficient of determination greater than 0.912. Further, the free shrinkage of HW pulps is a few percent higher than that of SW pulps at a given density (Fig. 3). It is clear that free shrinkage of all pulps gradually increases, about 4%, by increasing apparent density from 0.5 to 0.7 g/cm³. The Mercer spruce and Eno birch pulps exhibited the highest free shrinkage, 15.6% and 18.2%, respectively, whereas the spruce/pine blend, eucalyptus, and Star spruce pulps exhibited the lowest free shrinkage among other pulps. From fiber geometry measurements, both Mercer spruce and Eno birch pulps have the lowest cell wall thickness, 4.17 and 2.19 µm, respectively. On the other hand, the spruce/pine blend, eucalyptus, and Star spruce pulps have the highest cell wall thickness at 8.03, 6.27, and 4.46 µm, respectively. It is well accepted that fiber wall thickness directly influences fiber flexibility (deformability) [29,31-35], and thereby indirectly influences the development of interfiber bonding. Paavilainen [32] reported that increase in cell wall thickness can decrease fiber collapsibility. Increases in cell wall thickness can affect free shrinkage negatively by reducing the total surface area of the fibers for bonding, as shrinkage forces less transmitted in the sheet. This is in agreement with Nanko and Wu [24], who reported that thick-walled fibers shrank less than thin-walled fibers when the sheet is freely dried. However, when the sheet restrained, the longitudinal shrinkage of thick-walled fibers was more than thin-walled fibers. Also, no meaningful influence of length and width of pulp fibers on the free shrinkage of handsheets is observed. However, it can be stated that the Lapponia pine pulp fiber with the fiber length of 3.79 mm, which is more than triple that of Eno birch pulp fiber length of 1.02 mm, exhibits lower shrinkage, about 7% at the same density of 0.84 g/cm³ (the last data point in **Fig. 3**). As shown in Fig. 3, there is a very rapid increase in free shrinkage at higher densities for the Eno birch and Mercer spruce pulps. The free shrinkage of the handsheet formed from the Eno birch pulp increases from 10.2% to 18.2%, while the apparent density changes from 0.77 to 0.84 g/cm³. The SR value changes from 41 to 76.



3. Free shrinkage plotted against apparent density (left); average free shrinkages of softwood (SW) and hardwood (HW) pulps (right). BP = bleached Lapponia pine; BB1 = bleached Eno birch; BS1 = bleached Mercer spruce; BB2 = bleached Södra gold birch; UBSP = unbleached spruce/pine; BE = bleached eucalyptus; BS2 = bleached Star spruce.



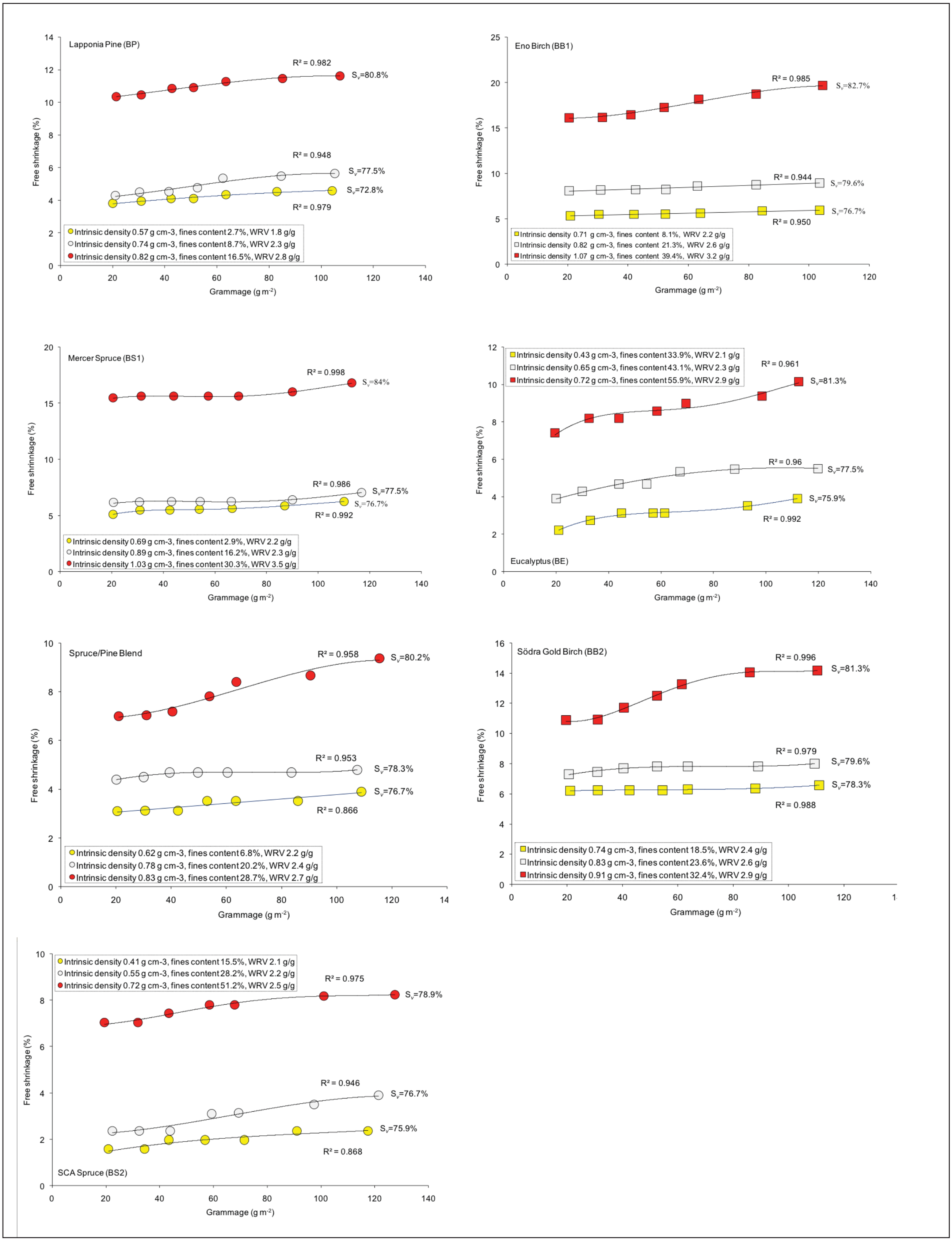
4. Free shrinkage plotted against fines content (left); WRV plotted against fines content (right).



5. Free shrinkage plotted against WRV.

The free shrinkage of the handsheet formed from the Mercer spruce pulp increases from 11.7% to 15.6%, whereas the apparent density changes from 0.82 to 1.00 g/cm^3. The SR value changes from 77 to 86.

Free shrinkage is plotted against fines content in **Fig. 4**. As anticipated, for a given pulp free shrinkage increases with fines content. There are, however, marked differences among the different pulps. For example, the eucalyptus and Star spruce pulps have high fines content, but not particularly high free shrinkage. The Star spruce and Eno birch pulps with the same fines content, 28%, exhibited different free shrinkage, 3.1% and 10.2%, respectively. It can be noted that the high fines content of these pulps has not resulted in particularly high apparent densities. The free shrinkages of the Lapponia pine and Mercer spruce pulps are influenced significantly by the amount of fines retained in the sheet. For the Lapponia pine pulp, for the last two data points in Fig. 4, the free shrinkage increases from 6.2% to 11.3% by increasing the fine contents from 11.2% to 16.5%, whereas for the Mercer spruce pulp the free shrinkage increases from 11.7% to 15.6% by increasing the fines content from 28.5% to 30.3%. It is clear the fines content of the last data point for the Mercer spruce pulp is almost double that of the Lapponia pine. However, the Star spruce pulp with the largest increase in the amount of fines, from 36.4% to 51.2%, which is more than triple that of the Lapponia pulp fines content, exhibits the smallest increase in free shrinkage, from 5.9% to 6.3%. It is the same for the HW pulps. For the last two data points in Fig. 4, the free shrinkage for the Eno birch pulp increases from 10.2% to 18.2%, whereas the fines content changes from 28.1% to 39.4%. For the Södra gold birch pulp, the free shrinkage increases from 12.0% to 13.3%, whereas the fines content changes from 28.4% to 32.4%. On the basis of the last data point in Fig. 4, the Eno birch pulp exhibits 4.9% higher shrinkage compared with that of the Södra gold birch pulp as a result of an increase in fines content, which is 11.3%. However, for the eucalyptus pulp with



6. Free shrinkage plotted against grammage for the handsheets formed from all pulps.

the largest increase in the amount of fines, from 46.0% to 55.9%, the free shrinkage changes from 6.3% to 9.0%.

Figure 4 also shows WRV plotted against fines content. As expected, for all pulps the WRV increases with fines content. Further, there is a good linear relationship between the WRV and fines content of the all pulps ($R^2 = 0.95$), except the Mercer spruce pulp. Because fines can absorb more water, they swell more than fibers. Salmén et al. [30] reported that WRV of fines is greater than that of fibers; this was in agreement with Sampson and Yamamoto [26], who later showed that the WRV of fines is about double that of the fines-free pulp. The dependence of free shrinkage on WRV is shown in **Fig. 5**, which exhibits a strong positive correlation. It is clear that by increasing the WRV from 2.0 to 2.5 g/g, the free shrinkage of all pulps increases around 6%. The Star spruce pulp exhibited the lowest WRV among all pulps. Sampson and Yamamoto reported that the influence of fines on free shrinkage is not attributable to their greater WRV; at most, this is likely to be a second-order effect [26]. Substituting WRV for parameter m in (Eq. 1), a value is obtained for the volumetric shrinkage of a fiber, S_v, of 72% at the lower end of the observed range (i.e., $m = 1.5$, and a value of $S_v = 84\%$ at the higher end of the observed range, $m = 3.5$). So, the relative change in S_v across the range of samples is around 12%, which is insufficient to induce the observed relative change in free shrinkage, which is around 900%. This is in disagreement with the conclusion made by Salmén et al. [30] who reported that the higher shrinkage of sheets containing fines is a consequence of the greater WRV of fines compared to that of fibers.

From Figs. 3 and 4, it is clear that the general dependence of free shrinkage on density and fines content is the same for each pulp, but there is a difference in the absolute values. The effect of grammage on free shrinkage is now considered. Typical data are shown in **Fig. 6**; data were obtained for all pulps. There is little difference between the free shrinkages over the range of grammages at low densities, whereas by increasing the density, a significant difference is observed and it is consistent for all pulps. However, some pulps exhibited very strong grammage dependence, such as the eucalyptus, spruce/pine blend, and Södra gold birch pulps, especially at higher densities. For most of the pulps, the free shrinkage remains almost constant by increasing grammage up to 40 g/m^2, but when grammage goes higher than this, the free shrinkage increases meaningfully. Further, some pulp samples with different densities and grammages exhibited the same free shrinkage. The Lapponia pine pulp with intrinsic density of 0.57 g/cm^3, which corresponds to grammage of 83.1 g/m^2, has the same free shrinkage, 4.5%, as a sample with intrinsic density of 0.74 g/cm^3 and grammage of 30.4 g/m^2. Another example is the eucalyptus pulp with intrinsic density of 0.43 g/cm^3, which corresponds to grammage of 112.1 g/m^2, that has the same free shrinkage, 3.9%, as a sample with intrinsic density of 0.65 g/cm^3 and grammage of 20 g/m^2.

Comparing the Lapponia pine and Södra gold birch pulps, it is clear that there is little difference between the free shrinkages over the range of grammages for the handsheets formed from the Lapponia pine pulp. The volumetric shrinkages (S_v) of the samples with different intrinsic densities are estimated by substituting WRV for parameter m in Eq. 1. At low intrinsic densities of 0.57 and 0.74 g/cm^3, the difference in volumetric shrinkage is 4.7%; however, the difference in free shrinkage is 0.5% at low grammages and 1.1% at higher grammages. For the two samples with intrinsic densities of 0.74 and 0.82 g/cm^3, the difference in their volumetric shrinkage is 3.2%, whereas the difference in their free shrinkage is about 6.2%. The difference in free shrinkage in handsheets with densities of 0.57 and 0.8 g/cm^3 and 0.74 and 0.82 g/cm^3 is almost the same, 6.1% and 6.2%, respectively. The difference in volumetric shrinkage of handsheets with intrinsic densities of 0.57 and 0.82 g/cm^3 and 0.74 and 0.82 g/cm^3 is different, 7.9% and 3.2%, respectively. Therefore, the influence of WRV is limited. For the handsheets formed from the Södra gold birch pulp, at low densities, there is little or no influence of grammage on free shrinkage, though as density increases, a significant dependence is seen. This is consistent with the findings of Sampson and Yamamoto [26] for pulp with and without fines. Interestingly, for the handsheets with low intrinsic densities, 0.74 and 0.83 g/cm^3, the difference in free shrinkage and volumetric shrinkage is almost the same, 1.41 ± 1%.

CONCLUSIONS

Overall, the role of different fiber types on the free shrinkage of handsheets is explored within this paper. The influence of density, fines content, WRV, and grammage on the free shrinkage of handsheets formed from several SW and HW pulps are presented. A nonlinear dependence of free shrinkage on apparent density is observed, though in general the free shrinkage of HW pulps is a few percent higher than that of SW pulps at the same density. Both fines content and WRV have a positive influence on the free shrinkage of handsheets. In spite of the fact that free shrinkage increases with fines content for a given pulp, from volumetirc shrinkage of a fiber, this dependence is not influenced significantly by WRV, which is reported to be greater for fines than it is for fibers. In addition, a high fines content does not imply high shrinkage, as evidenced by the eucalyptus and Star spruce pulps studied here. Considering the fiber geometry measurements, fiber wall thickness is the most influential factor because free shrinkage is strongly affected by it. According to the results, pulp fibers with a thicker cell wall are more resistant to sheet shrinkage, as pulp fibers with a thinner cell wall exhibit higher shrinkage over the range of grammages compared with pulp fibers with a thicker cell wall. The free shrinkage of the handsheets formed from HW pulps at low densities is almost equal to the volumetric shrinkage of that fiber over the range of grammages. This is not consistent for the SW pulps. Finally, free shrinkage of handsheets formed from all pulps is sensitive to sheet grammage. There is a little difference between free shrinkages over the range of grammages at low densities, whereas by increasing the density, a significant difference is observed and it is consistent for all pulps. It is also found that free shrinkage of handsheets formed from HW pulps is more sensitive to sheet grammage compared with that of SW pulps. In agreement with Sampson and Yamamoto [26], it is observed that the plots of shrinkage against grammage do not pass through the origin. The preliminary understanding is that the longitudinal shrinkage of fibers represents a lower boundary on the shrinkage of the network. Future work is in hand to investigate this hypothesis. It is also found that some of the pulp samples with the same intrinsic density and WRV exhibit different free shrinkage over the range of grammages, which needs to be investigated further. **TJ**

LITERATURE CITED

1. Sampson, W.W., *Int. Mater. Rev.* 54(3): 134(2009).
2. Biermann, C.J., *Handbook of Pulping and Papermaking*, Academic Press, 1996, p. 13.
3. Smook, G.A., *Handbook for Pulp and Paper Technologists*, 2nd edn., Angus Wilde, 1992, p. 264.
4. Keränen, J., Myllys, M., and Kiiskinen, H., *Appita J.* 62(2):146(2009).
5. Lindem, E., *TAPPI Int. Pap. Phys. Conf., Proc.*, TAPPI Press, Atlanta, GA, USA, 1991, p. 327.
6. Niskanen, K., *Paper Physics*, TAPPI Press, Atlanta, 1998, p. 222.
7. Wahlström, T. and Lif, J.O., *TAPPI Int. Pap. Phys. Conf., Proc.,* TAPPI Press, Atlanta, 2003, p. 169.
8. Wadhams, K.R., I'Anson, S.J., James, D.M., et al., *Pap. Technol.* 32(1): 36(1991).
9. Viitaharju, P.H. and Niskanen, K.J., *Tappi J.* 76(8): 129(1993).
10. Hoole, S.M., I'Anson, S.J., Ora, M., et al., *Pap. Technol.* 40(10): 63(1999).
11. Wedel, G.L., *TAPPI Annu. Meet. Proc.*, TAPPI Press, Atlanta, 1989, p. 23.
12. Pulkowski, J.H., *Pulp Pap. Can.* 94(6): 48(1993).
13. Wahlström, T., *TAPPI J.* 31(5): 31(1999).
14. Constantino, R.P.A., I'Anson, S.J., and Sampson, W.W., in *Adv. Pap. Sci. Technol., Trans. Fundam. Res. Symp.,13th*, Pira International, Leatherhead, U.K., 2005, p. 283.
15. Nanko, H. and Oshawa, O., in *Fundam. Papermaking Mater., Trans. Fundam. Res. Symp., 9th*, Pira International, Leatherhead, U.K., 1989, p. 783.
16. Silvy, J., *Paper Technol.* 12(5): 377(1971).
17. Htun, M. and Ruvo, A., in *Fiber-Water Interactions in Papermaking, Trans. Fund. Res. Symp., 6th*, Pira International, Leatherhead, U.K., 1977, p. 477.
18. Htun, M. and Ruvo, A., in *The Role of Fundamental Research in Papermaking, Trans. Fund. Res. Symp., 7th*, Pira International, Leatherhead, U.K., 1981, p. 385.
19. Nanko, H., Asano, S., and Oshawa, J., *TAPPI Int. Pap. Phys. Conf., Proc.*, TAPPI Press, Atlanta, 1991, p. 365.
20. Page, D.H. and Tydeman, P.A., in *The Formation and Structure of Paper, Trans. Fund. Res. Symp., 2nd*, Pira International, Leatherhead, U.K., 1961, p. 397.
21. Hansson, T., Fellers, C., and Htun, M., in *Fundam. Papermaking Mater., Trans. Fundam. Res. Symp., 9th*, Pira International, Leatherhead, U.K., 1989, p. 743.
22. Karlsson, M., *Papermaking Part 2: Drying*, Fapet Oy, Helsinki, 2000, p. 16.
23. Baum, G.A., in *Prod. Papermaking, Trans. Fund. Res. Symp., 10th*, Pira International, Leatherhead, U.K., 1993, p. 1.
24. Nanko, H. and Wu, J., *TAPPI Int. Pap. Phys. Conf., Proc.*, TAPPI Press, Atlanta, 1995, p. 103.

ABOUT THE AUTHOR

I chose this topic to research because free shrinkage is a fundamental property of any paper web. A better understanding of this property of a furnish can lead to a better understanding of the factors affecting cross-machine direction (CD) shrinkage. By investigating the influence of several softwood and hardwood pulp fibers on the free shrinkage of handsheets, this work contributes to a wider understanding of the mechanism of free shrinkage during the drying process.

Obtaining a stable temperature was the key for gaining reliable results from examining the handsheets, which dried freely. To achieve this, I followed the necessary procedures, such as using temperature control devices and making sure air flow was controlled during the drying process in the laboratory environment.

One of the findings was that a high fines content does not imply high shrinkage, as evidenced by the eucalyptus and Star spruce pulp studied.

Interestingly, fines content has a positive influence on the free shrinkage of handsheets. However, this is not significantly influenced by their greater water retention value. Free shrinkage of handsheets formed from hardwood pulps is more sensitive to sheet grammage.

Mayeli

This work benefits the industry by providing wider and deeper knowledge about free shrinkage of isotropic paper sheets, which is the main cause of the CD shrinkage profile. The next step is the investigation of the longitudinal shrinkage of fiber on the shrinkage of the network.

Mayeli was a Ph.D. researcher at the University of Manchester, Manchester, UK. Email Mayeli at nader.mayeli@hotmail.com.

25. Salmén, L. and Berthold. J., in *Fundam. Papermaking Mater., Trans. Fundam. Res. Symp., 11th*, Pira International, Leatherhead, U.K., 1997, p. 683.
26. Sampson, W.W. and Yamamoto, J., *Appita J.* 64(1): 76(2011).
27. Nanri, Y. and Uesaka, T., *Tappi J.* 76(6): 62(1993).
28. Vainio, A., Kangas, J., and Paulapuro, H., *J. Pulp Pap. Sci.* 33(1): 29(2007).
29. Uesaka, T., and Moss, C., in *Fundam. Papermaking Mater., Trans. Fundam. Res. Symp., 11th*, Pira International, Leatherhead, U.K., 1997, p. 663.
30. Salmén, L., Boman, R., Fellers, C., et al., *Nord. Pulp Pap. Res. J.* 2(4): 127(1987).
31. Steadman, R. and Luner, P., in *Papermaking Raw Mater., Trans. Fund. Res. Symp., 8th*, Pira International, Leatherhead, U.K., 1985, p 311.
32. Paavilainen, L., *Pap. Puu* 72(9): 689(1993).
33. Broderick, G., Paris, J., Valade, J.L., et al., *Tappi J.* 79(1): 161(1996).
34. Wimmer, R., Downes, G.M., Evans, R., et al., *Holzforschung* 56(3): 244(2002).
35. Pulkinnen, I., Fiskari, J., and Alopaeus, V., *BioResources* 4(1): 126(2009).