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DRYING INDUCED TENSION VARIATION IN PAPER WEB

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ABSTRACT

Laboratory drying experiments were done with a standard tensile testing device to study basic mechanisms of moisture induced tension variation. Also, pilot machine experiments were done to compare with the laboratory tests. The results show that the tension variation of paper is generated by a combined effect of moisture variation and straining during drying. The laboratory experiments indicate that tension variation is induced by strain differences in paper web. Tensile stiffness, which is affected most by wet straining, is almost constant between areas of different initial moisture contents. On the other hand, pilot tests showed only small effect of the initial moisture variation. In rewet experiments it is found that dried-in strain is recovered when paper is rewetted.

INTRODUCTION

On-machine integrated coating and calendering processes have set tight constraints on tension variation in a paper web. Single weak spot simultaneously with a tension surge can destroy the performance of the whole papermaking line. In addition, on-line process does not include any dampening stage typical for conventional off-machine finishing processes. In a machine roll, moisture and temperature variation can even out. Also, the local stress concentrations are reduced due to long period for stress relaxation.

The recent development of the wet press and drying sections of paper machine allows higher web speed. The runnability of paper machine is increased by closing all the open draws and with other new components. Due to this development, the control over the drying section parameters has revealed new potential. The magnitude of wet and dry strain levels can be largely varied.

Several researchers have studied fiber drying. The transverse shrinkage is typically large during drying, 20–30%, while the longitudinal shrinkage is small, 1–2%. Weise [1] divides fiber shrinkage into two phases. First, large intra-fiber cell wall pores are dewatered and free and bound freezing water [2,3] is removed from fibers. This starts when fiber saturation point is passed in drying and continues up to about 75% dry solids content. The removal of free and bound freezing water causes inter-lamellar pores to close or to tighten. Most of deformations occur to flatten fibers. The second phase of fiber shrinkage starts when tightly bound non-freezing water [2,3] is removed from fibers. Nanko et al. [4] observed consequent collapse in fiber width around 85–90% dry solids content (fiber collapse point). On the other hand, Weise [1] found relatively large variation between separate fibers in the removal of non-freezing bound water around 70–90% dry solids contents. Also, the shrinkage of fibers was not always as abrupt as in Nanko et al. [4] experiments.

Jentzen [5] dried single fibers under tension. He observed that wet elongation of fibers is frozen into fiber wall structure during drying. Larger tension induced larger increase in axial crystallity orientation and tensile stiffness. Thus, it is probable that fiber fibril angle decreased. Fiber properties were recovered to the initial level after rewetting the dried fibers. Jentzen also observed a sudden collapse of fibers during drying. No further deformations were observed after the collapse.

The removal of inter-fiber water increases surface forces that compact the network (Campbell effect) [6]. These forces are rather strong. However, no real inter-fibre bonds occur below about 50% dry solids content, while fiber network is still wet and fibers are swollen [7,8]. In bonded fiber regions the lateral shrinkage of crossing fibers exerts compressing forces upon the counter fibers. Consequently, the counter fibers are compressed in length direction [7]. In restraint drying bonded fiber segments induce straightening and straining of free fiber segments so that fibers are activated [8].

In restraint drying the general shape of drying tension curves is logistic. Drying tension increases slowly below about 60–70% dry solids content, because dewatering occurs only from the large intra-fiber pores. A deep increase in drying tension occurs typically at 75–85% dry solids content. This is due to fiber shrinkage and collapse, which tranforms to network activation.

Drying tension saturates above the fiber collapse point when the final drying stage of the structure is frozen. Hydrogen bonds are formed between adjacent hydroxyl groups of cellulosic material and hemicellulose regions changes from a gel state to a solid material [8].

Several studies on uniaxial wet straining can be found in literature [9–14]. Wet straining enforces network activation and Jentzen effect [5,8]. More even strain distribution between activated fibers [15] and larger elastic modulus of fibers increase tensile stiffness of paper. In biaxial drying Wahlström and Fellers [16] found that cross direction load affect little paper properties in perpendicular direction if the perpendicular strain is fixed.

The combined effect of moisture variation and several consecutive draws applied during drying is not well known. At certain level of wet straining drying tension is typically almost constant below about 55% dry solids content. Thus, restraint drying and probably also wet straining induce little differences in rheological properties of dry paper between the areas of web with small initial moisture variation. If draws are applied in the middle of drying, while drying tension has largest gradient, material properties are affected most between the areas of different moisture contents. Thus, it is plausible that the cross direction tension profile is affected most by the draws in the middle of drying and the end properties of dry paper vary most.

In this study several strain cycles were applied on samples with different initial dry solids contents. Thus, a more paper machine like drying process was obtained than in ordinary laboratory tests. Also, pilot machine trials were done to compare the results.

Currently, tension profile is the most important on-line measurement technique available to estimate the rheological properties of paper web. Thus, special emphasis is paid to understand how moisture affects cross direction MD tension variation of paper web. Also, other parameters, such as temperature, formation and orientation can induce tension variation of paper web. In addition, tension varies due to larger drying shrinkage of web edges than center parts [17,18]. However, only the effect of moisture is considered here.

EXPERIMENTAL

Sample material

Laboratory sheets were made from 30 : 70 mixture of bleached once-dried softwood kraft and bleached TMP. The kraft was beaten to SR-value 25 in a Walley-Hollander refiner and the TMP was taken from a mechanical pulp line of finnish paper mill. The freenes of the TMP was 35.

A full automatic handsheet robot (M/K Systems) was used to make non-oriented 30*30 cm^2 laboratory sheets. The grammage of dry paper was 60 g/m^2. After wet pressing the dry solids content of the sheets was about 35%. 5*15 cm^2 specimens were cut from the wet pressed sheets and were used later in drying tests. In pilot trial wet pressed LWC pilot machine paper were used.

Laboratory drying

A standard tensile testing machine (Alwetron TCT5) was used in drying to have one dimension uniaxial drying restraint and to measure drying tension. Specimens were dried with two infrared heaters and the dry solids content of paper was measured with an infrared sensor (Infrared Engineering MM55E). The temperature of paper increased from 23°C to about 65°C during drying.

The clamping areas of the specimen were dried with an iron to avoid specimen tearing during drying. The length of the wet area in the middle of the specimens was 12 cm. After that specimens were attached to the jaws and were let to dry up to 45% or 48% dry solids content before 1.5% wet strain. After that four draws according to a full factor experimental design with two strain levels of each draw was performed. The dry solids contents where the draws were applied were 51% and 54%, 66% and 70%, 80% and 85%, 91% and 94%. Respectively, the strain levels were 0.1% or 0.5%, 0.1% or 0.5%, 0.1% or 0.5%, 0.1% or 0.3%.

Pilot drying

Pilot machine was equipped with three separate drying groups plus an impingement unit. It was possible to adjust four different draws of paper web. The draws were applied at 44%, 54%, 58% and 91% dry solids contents. Thus, the first three draws were practically wet straining, while the last draw was applied after the network structure was already dried-in almost completely. This was due to a powerful impingement unit under which paper dried on a drying cylinder from 60% to 90% dry solids content.

In the drying pilot wet, 55-cm wide paper rolls were used. Right after the unwinder of the drying pilot a 10-cm wide, –3% moisture streak was sprayed on paper 10 cm off the center axis of the web. The reference base paper was taken equally from the other side of center axis. After spraying the streak a full factor design with two levels of the four draws was applied. The corresponding strain levels were 0.2% or 0.35%, 0.1% or 0.5%, 0.1% or 0.5% and 0.3% or 0.6%.

Mechanical testing

Tensile stiffness and breaking strain were measured from 120*50 mm^2 specimens. Strain rate was 0.17%/s. Elastic strain was measured from the amount of recoverable strain. The unloading rate was 0.05%/s. In some cases tension level is divided with tensile stiffness to calculate elastic strain.

In relaxation tests the initial strain rate of 100*15 mm^2 specimens was 0.17%/s. Relaxation time was chosen to correspond 0.09%/s strain rate. For example, with 1% and 2% initial strains the relaxation times were 5.1 s and 10.2 s.

In rewet experiments dry paper specimens were rewetted to 40% dry solids content between blotters. After that the specimens were moved onto drying plates and redried. The specimen length and specimen width were measured before and after the rewet from scanned black and white images. A 1200 dpi desktop scanner was used.

RESULTS

Drying shrinkage and drying tension

When paper dries it attempts to shrink due to inherent properties of raw material. In free drying the level of shrinkage depends on paper grade and is typically relatively large 2–10% [16].

Figure 1a shows a drying tension curve in uniaxial restraint drying of sample that shrinks 3.4% in free drying. Tensile stiffness and shrinkage induced elastic strain maintain the drying tension. Then both, stiffness and strain, increase vs. drying (Figure 1b). However, the shape of the drying tension curve is practically defined by stiffness, because elastic strain is linear vs. drying.

According to Figure 1b elastic strain is small, 0.2%, in dry paper. Therefore, the 3.4% potential shrinkage strain is mostly frozen as nonrecoverable strain of paper during drying. This plastic strain is due to changes in fiber network structure. Free fiber segments straighten under shrinkage tension and the number of load carrying fiber segments increases [8].

Effect of wet straining

Figure 2 compares drying tension curves for different wet strain levels to dry solids content of paper. The initial peak tension right after wet straining against the wet strain level (Figure 3) is the ordinary stress-strain curve in tensile test of wet paper. The tension curve is nonlinear right from small

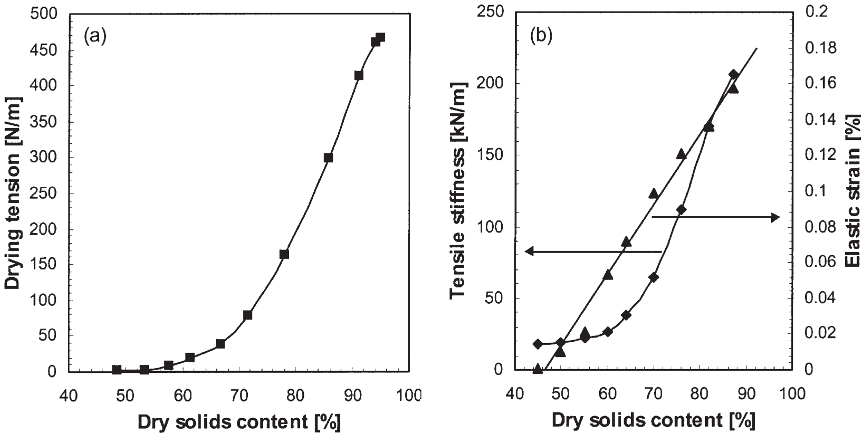


Figure 1 Drying tension (a), tensile stiffness and elastic strain (b) vs. dry solids content in uniaxial restraint drying.

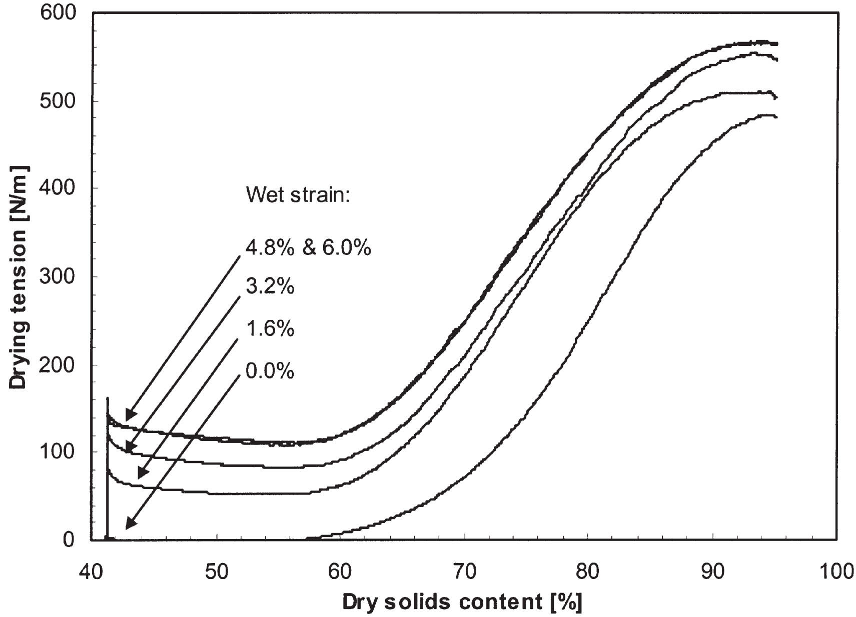


Figure 2 Drying tension vs. dry solids content for different wet strain levels.

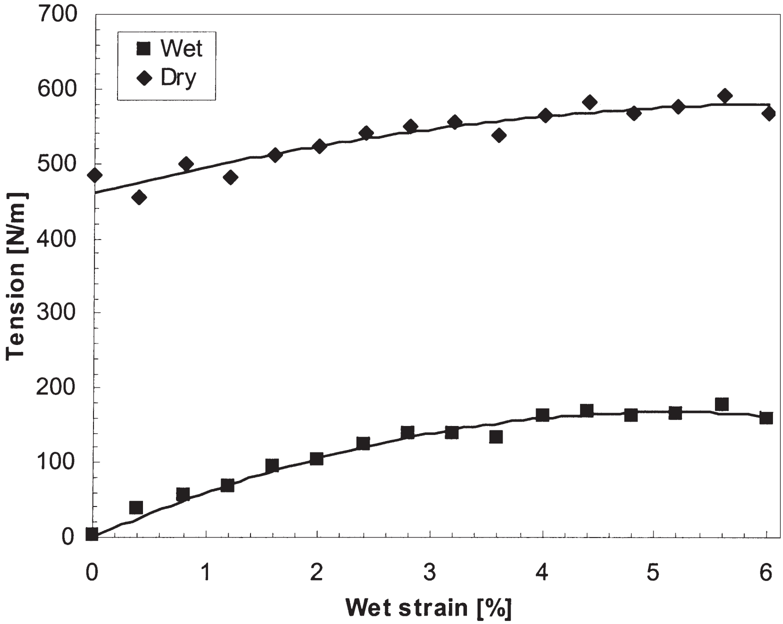


Figure 3 Tension of wet and dry paper vs. the level of wet strain.

strain values. However, a small level of wet straining (0–3%) increases tension clearly. At large level of wet straining (4–6%), tension saturates to constant level.

The overall shape of the drying tension curves in Figure 2 is the same. The different wet straining curves are separated all the way from wet to dry paper. The absolute tension differences are almost the same in wet paper and dry paper, as also shown in Figure 3. Because tensile stiffness is much larger in dry paper than in wet paper (Figure 1b), the elastic strain of wet strained samples must decrease during drying.

Figure 4 shows that elastic strain of wet paper increases vs. wet straining (elastic strain is calculated by dividing wet tension level with wet tensile stiffness). The maximum level of elastic strain is 1.1%. The rest of the wet strain is plastic. In dry paper, the all samples have 0.2% recoverable strain after drying. It is the same as in restraint drying in Figure 1b. This explains why in Figure 3 the relative differences of drying tensions are smaller than the differences between wet tensions. The elastic part of wet straining is transformed completely as nonrecoverable strain of paper during drying and the different

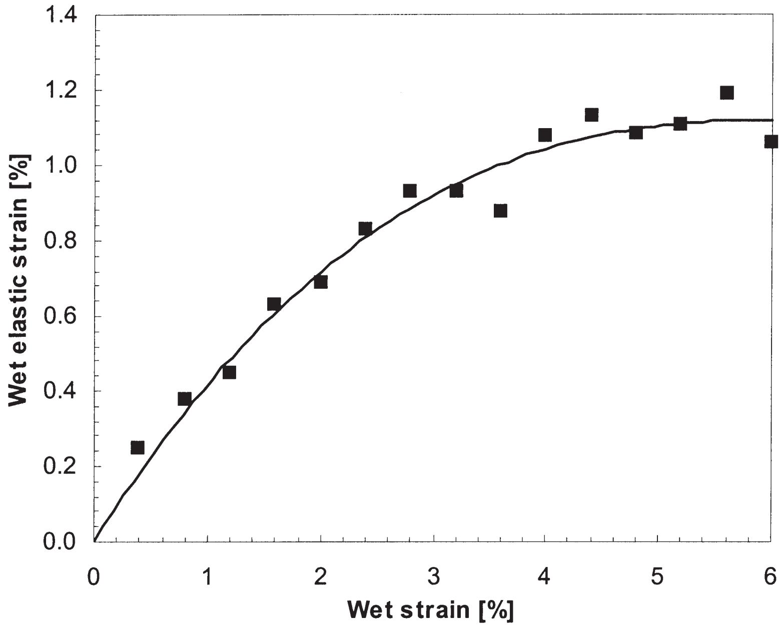


Figure 4 Wet elastic strain vs. wet strain at 41% dry solids content.

tensions between dry paper samples come from differences in tensile stiffness.

The beginning part of the drying tension curves in Figure 1a indicates that part of the tension induced by the wet straining decreases due to relaxation. It is shown that the relaxed stress is larger the larger is the initial strain level [19]. Thus, relaxation, in addition to elastic strain, can affect drying tension. Also, it is shown that in relaxation elastic strain transforms to nonrecoverable plastic strain [19,20]. Therefore, relaxation in addition to frozen strain is possible mechanism that explains the loss of wet elastic strain during drying.

Recoverable elastic strain was measured from wet paper 60s after 4% wet strain (at 41% dry solids content). The elastic strain was 0.8%, which is 0.2% smaller than the initial elastic strain at the moment of wet straining. This indicates a small tranformation between the elastic and plastic strain components due to relaxation. However, specimens dried to 45% dry solids content during the test, which may also affect the result.

Figure 5 shows another results of relaxation vs. different initial strain levels for 48% and 72% dry solids content. The relaxed tension, σ_1, vs. initial strain seems to follow the maximum tension, σ_0, in other respects but the tension

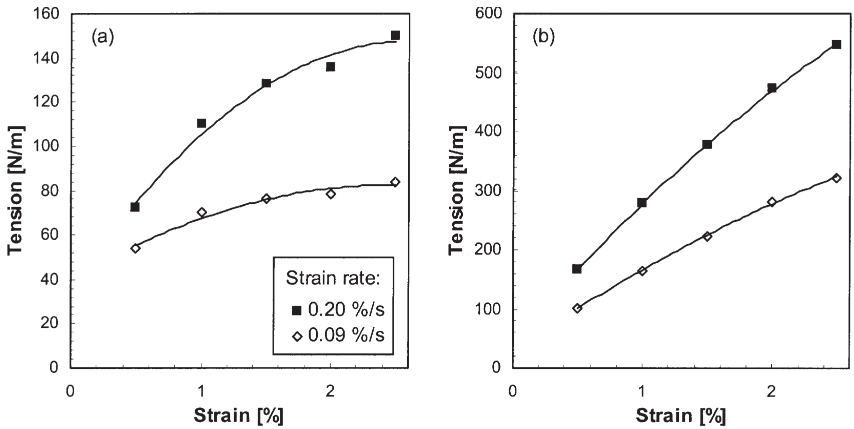


Figure 5 Maximum tension and relaxed tension vs. initial strain. Specimens are restraint dried to 48% (a) and 72% (b) dry solids content before 0.17%/s straining. Relaxation results correspond 0.09%/s strain rate.

values are smaller. The ratio σ_1/σ_0 decreases when initial strain level increases. In wet paper (48% dry solids content) σ_1/σ_0 is 75% for 0.5% strain and 56% for 2.5% strain. Respectively, for 72% dry solids content σ_0/σ_1 decreases from 61% to 59% vs. initial strain.

Unfortunately, the recoverable elastic strain was not measured after relaxation. However, if it is assumed that tensile stiffness before and after relaxation is defined by the corresponding strain rates, the amount of plastic strain, ε_{pr}, generated in relaxation can be estimated from

$$\varepsilon_{pr} = \frac{\sigma_0}{E_0} - \frac{\sigma_1}{E_1} = \frac{\sigma_0}{E_0}\left(1 - \frac{\sigma_1}{\sigma_0}\frac{E_0}{E_1}\right) \tag{1}$$

where E_0 is tensile stiffness before relaxation and E_1 tensile stiffness after relaxation. In Figure 5 the ratio σ_1/σ_0 decreases vs. initial strain. Thus, it indicates that plastic strain increases in relaxation, if tensile stiffness is not changed.

The ratio E_1/E_0 can roughly be estimated by extrapolation the data in Figure 6 to elastic regime (~zero strain). Respectively, the ratio $E_1/E_0 \approx 0.80$–0.95 for the 48% sample, 0.70–0.75 for the 60% sample and 0.60–0.65 for the 72% sample. The corresponding differences between the initial elastic strain and the relaxed elastic strain, Equation (1), are 0.18–0.41%, 0.14–0.20% and

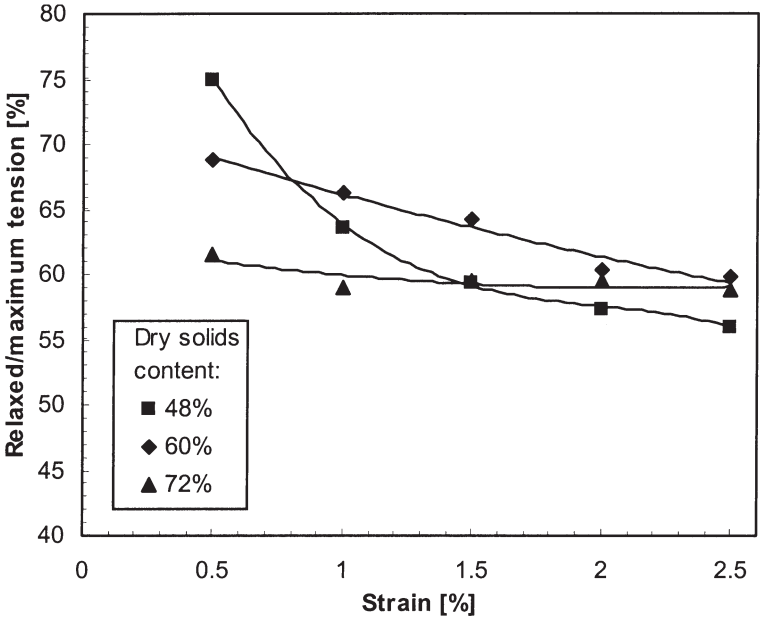


Figure 6 Ratio of relaxed tension to maximum tension vs. initial strain for different dry solids contents.

0.02–0.10% for 2.5% initial draw. Therefore, it is plausible that a part of wet elastic strain transforms to plastic strain due to relaxation during drying.

Next, as Jentzen [5] did for single fibers, dry paper specimens were rewetted to 40% dry solids content to find out if dried-in strains exist. Table 1 shows the relative length increments before and after the rewet. The restraint dried sample shrinks 1.0% after the rewet – well below the original length before

Table 1 Plastic wet strain and relative length of samples after drying and rewet.

Wet strain	Wet plastic strain	Length after drying	Length after rewetting
Restraint	–	3.2%	2.2%
3% at 60%	1.7%	6.2%	3.9%
4% at 41%	2.9%	7.2%	4.9%

drying. Thus, drying shrinkage of raw material induces dried-in elastic strain. Over 80% of it is frozen into network structure during drying.

The samples that were drawn 3% at 60% dry solids content and 4% at 41% dry solids content shrink 2.3% after the rewet. The differences between the lengths of wet strained samples and restraint dried samples after the rewet is almost the same as the plastic strain that is drawn in wet straining. The elastic strain caused by wet straining and by drying shrinkage is completely dried into network structure and this dried-in strain can be recovered by rewetting the specimens. Thus, in disagreement with the earlier results it seems that no additional permanent plastic strain above the wet plastic strain is introduced by relaxation. However, further tests are needed to ensure this.

Tension variation during drying

Next, the effect of moisture streaks on the cross direction MD tension variation is considered. If moisture variation exists at the beginning of drying but no draws are applied, moisture induces only little tension variation. Drying tension and tensile stiffness vary only slightly below about 60% dry solids content (Figures 1 and 2). Thus, tension profile is probably affected most in the intermediate level of dry solids content.

Not only material properties but also the initial moisture variation increases during drying. Figure 7 shows a simulation of dry solids content of

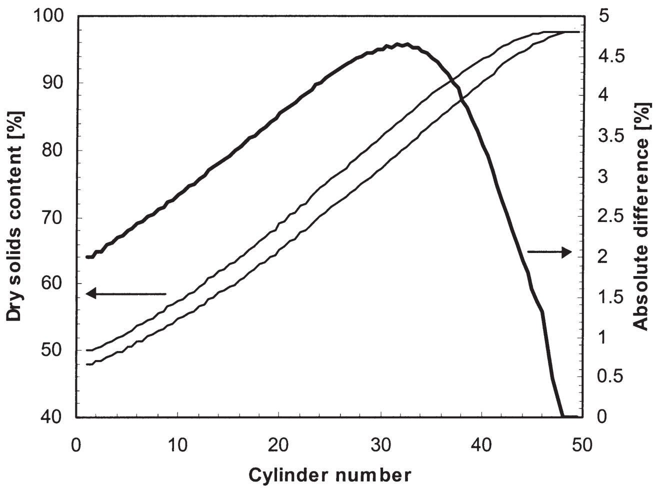


Figure 7 Simulation [21] of drying section of a paper machine.

paper in a drying section of an ordinary paper machine. The results are based on Heikkilä's drying model [21]. If the initial dry solids content is 50% with 48% moisture streak, the corresponding dry solids contents are 85% and 80% later at cylinder 33. According to Figure 2, this corresponds about ±10% variation in web tension.

In addition to wet strain at the end of press section, paper machine includes several small draws between the drying groups and between dryer cylinders and vac rolls. As the wet strain, also the other draws can affect tensile stiffness and elastic and plastic strain components of paper. Therefore, the total strain history of paper web from wet to dry paper is considered.

Small strain sequences were applied in laboratory tensile tester to simulate the drying section of real paper machine. Figure 8 shows examples of the experiments. During drying five draws were applied. The first, 1.5% wet strain, was constant. The other four intermediate draws had two levels and were applied at constant time after the beginning of test. In addition, two amplitudes of load-unload cycles were applied between the intermediate

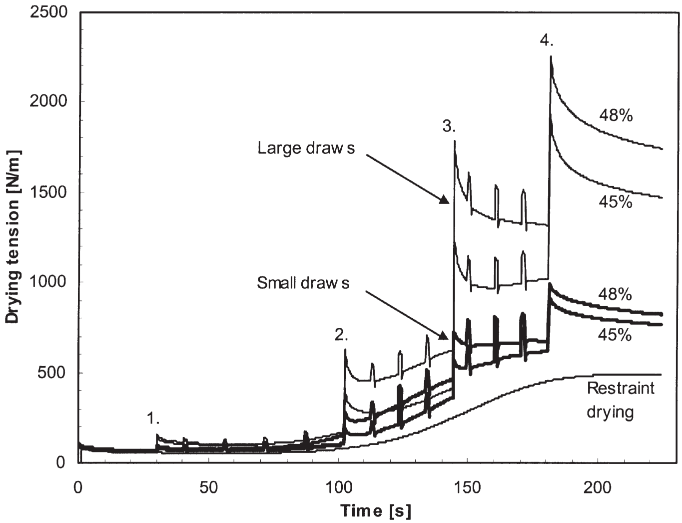


Figure 8 Drying tension vs. drying time. 1.5% wet strain is applied at 45% and 48% dry solids contents. Draws 1–4 are applied at dry solids contents 51% and 54% (0.1% or 0.5% strain), 66% and 70% (0.1% or 0.5% strain), 80% and 85% (0.1% or 0.5% strain), 91% and 94% (0.1% or 0.3% strain). The amplitude of small load-unload cycles is either 0.05% (shown in figure) or 0.1%.

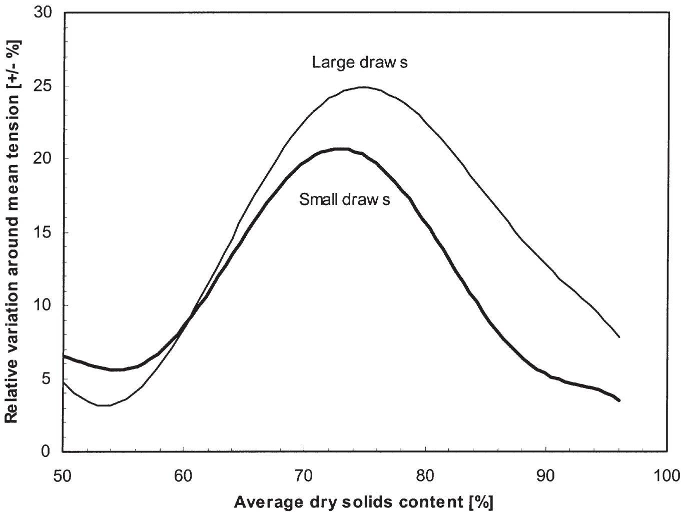


Figure 9 Relative tension variation around the mean tension vs. average dry solids content of paper. Large draws mean maximum level of the all draws 1–4 in Figure 8, and respectively small draws mean minimum level of the draws.

draws. Two different initial dry solids contents were used (45% and 48%) and a full factorial design of the draws was used in the tests.

Figure 9 shows the relative tension variation around the mean tension due to different initial dry solids contents. The curves are calculated from the tension curves in Figure 8. The relative variation is largest in the middle of the drying around 75% dry solids content, while the variation is almost the same at the beginning of drying and in dry paper. In the middle of drying tensile stiffness, elastic strain and dryness varies most between two areas of different initial dry solids content. The amplitude of the draws affects little relative tension variation. If the all draws are large, tension variation is about 5%-units larger than with small draws.

Figure 10 shows drying tension in dry paper for the all data points of the experiments. Although Figure 9 shows some effect of the amount of total strain, the overall variation of the data points induced by moisture seems quite insensitive to the amount of total strain during drying. Also, the amplitude of load-unload tension cycles does not affect the moisture induced variation. However, the large amplitude gives on the average 5% smaller drying tension, because it probably generates some plastic strain.

The relative tension variation between the samples with two initial dry

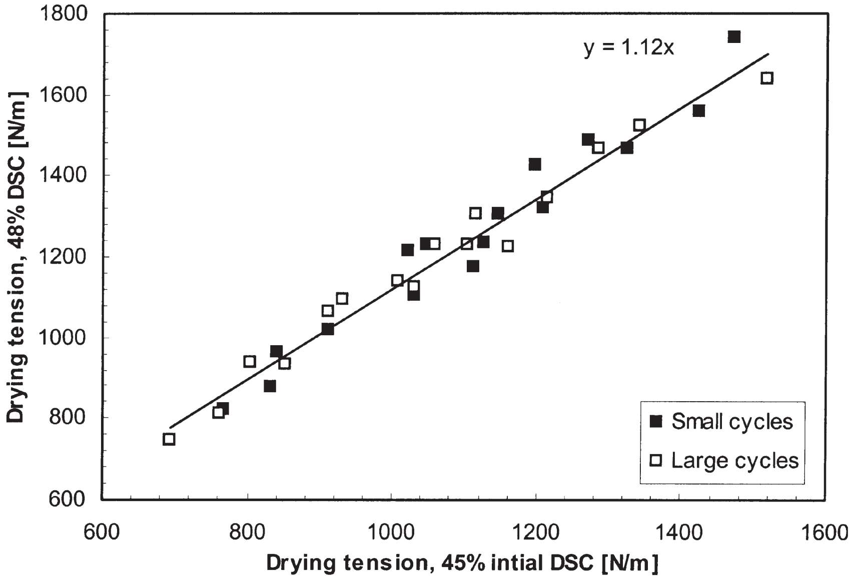
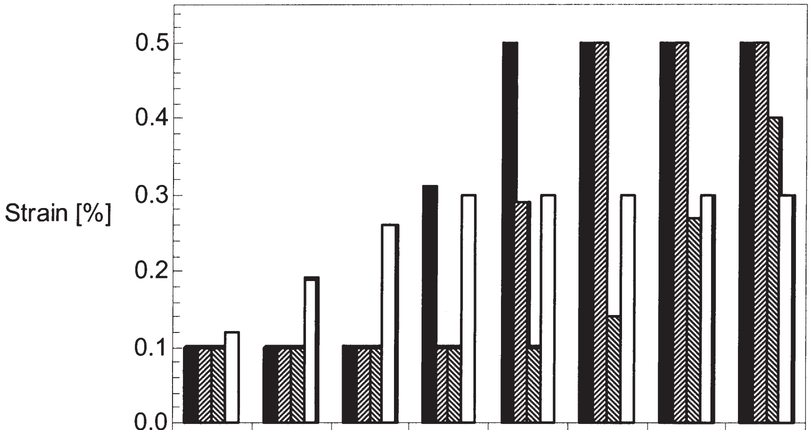


Figure 10 Drying tension of samples with 48% initial dry solids content vs. drying tension of the 45% samples.

solids contents varies between ±2.6–8.8% (around the mean value) for the all strain combinations. On the average, the 48% initial dry solids content gives 12% larger drying tension than the 45% dry solids content.

Figure 8 indicates that also relaxation affects tension variations. Thus, a small, 0.15%, draw was applied after drying and tension variation was measured 60 s after the straining. As expected [19], larger initial tension level gives larger stress relaxation. Therefore, tension variations decrease in relaxation. On the average, the 48% initial dry solids content gives 9% larger tension after relaxation than the 45% initial dry solids content.

A linear factorial model of the principal components (draws 1–4) is calculated to evaluate the effect of each draw on the properties of dry paper. The model explains almost all the variation of the results (coefficient of determination 0.95). Figure 11 shows the optimum setups of the draws during drying to minimize the tension variation of dry paper. Each draw can be varied most for target drying tensions 1100–1200 N/m. There the best setup gives ±4.0% variation in drying tension, while the worst setup has almost double as large, ±7.7%, variation. The last draw at 92% dry solids content affects least the variation. The draws between 65–85% dry solids content are the most critical



	800	900	1000	1100	1200	1300	1400	1500
■ Draw 1	0.10	0.10	0.10	0.31	0.50	0.50	0.50	0.50
▨ Draw 2	0.10	0.10	0.10	0.10	0.29	0.50	0.50	0.50
▧ Draw 3	0.10	0.10	0.10	0.10	0.10	0.14	0.27	0.40
□ Draw 4	0.12	0.19	0.26	0.30	0.30	0.30	0.30	0.30
Best/worst	0.93	0.72	0.60	0.52	0.54	0.63	0.76	0.90

Drying tension [N/m]

Figure 11 Optimal draws for fixed drying tensions to minimize tension variation in dry paper between areas of different initial dry solids contents (45% and 48%). The draws number 1, 2 and 3 are limited between 0.1–0.5% and the draw number 4 between 0.1–0.3%. Best/worst-ratio shows relative difference between tension and the variations of best and worst (not shown) setups.

and should be as small as possible. This result also applies to tension variation during drying (Figure 9).

Material properties

Figure 12 shows elastic strain and tensile stiffness of the two factorial analysis sample sets with different initial dry solids contents vs. each other. Elastic strain is measured as recoverable strain after drying and tensile stiffness is measured from the destrained specimens by standard tensile test. The average

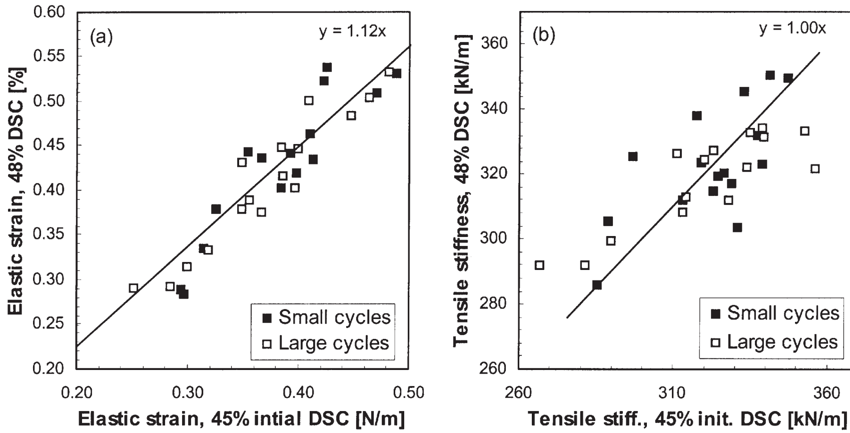


Figure 12 Elastic strain (a) and tensile stiffness (b) of the 45% and 48% sample sets after drying.

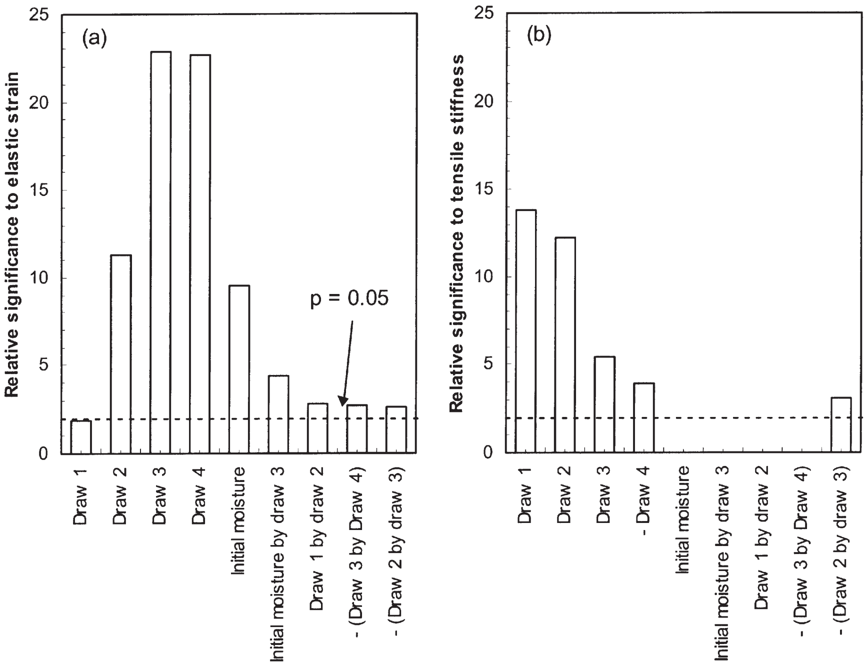


Figure 13 Statistical significance of factorial analysis parameters to elastic strain (a) and tensile stiffness (b) of the dry paper. Dashed line shows 95% level of confidence.

difference between the elastic strain of the 45% and 48% samples is the same as the average difference in drying tensions (Figure 10). On the other hand, the average tensile stiffnesses of the two dry solids contents in Figure 12b are the same. Therefore, it seems that tension variation between the areas of different initial dry solids contents is mainly caused by the different amount of elastic strain after drying and the variation of tensile stiffness has minor effect on tension variation.

Figure 13 shows the relative significance of the draws based on factorial analysis. In agreement with Figure 12 the initial dry solids content seems to affect elastic strain of dry paper but not tensile stiffness. The draws 3 and 4 increase most elastic strain and wet straining the least. This agrees with the earlier results: wet elastic strain is dried-in as nonrecoverable structural changes of fiber network. On the other hand, the plastic proportion of wet straining activates fiber network and increases tensile stiffness. Therefore, the draws 1 and 2 increase most tensile stiffness.

Figure 13 also shows some statistically significant interactions. For example, the effect of the third draw on elastic strain is larger with the 48% initial dry solids content and smaller with the 45% initial dry solids content. However, almost all the variation of the results can be explained only with the principal components.

Finally, the rewet test in Table 1 was repeated for some of the samples with the 48% dry solids content to check how the draws affect the rewet shrinkage. In addition to vertical length in the draw direction also the lateral width was measured. Figure 14 shows the dimensions after drying and after rewet. The samples shrink 1.2–1.6% in vertical direction and expand 1.3–1.6% in lateral direction. Thus, dried-in strain is seen in both directions.

All the data points in Figure 14 fall close to the same trendline. Also, the free shrinkage point is on the same trendline. The slope of the trendline is an apparent Poisson ratio of drying. For example, in restraint drying 3.4% of lateral shrinkage is due to shrinkage potential of raw material and 3.7% is due to tension induced Poisson contraction. The slope is large compared to ordinary Poisson ratios of paper. However, Viitaharju and Niskanen [18] measured Poisson ratios of the same order in a pilot paper machine.

Factorial analysis was used to evaluate the effect of the draws on rewet dimensions. The draws 1 and 2 affect most the dried-in strain (relative effects ~ 30% and 60%). It is plausible that the draws applied above the level of fiber collapse point do not affect dried-in strain, because the structure of fiber network is already frozen. On the other hand, in wet paper inter-fiber bonding areas have limited capability to transfer stress to strain fibers axially. Thus, it seems reasonable that the second draw has the largest effect.

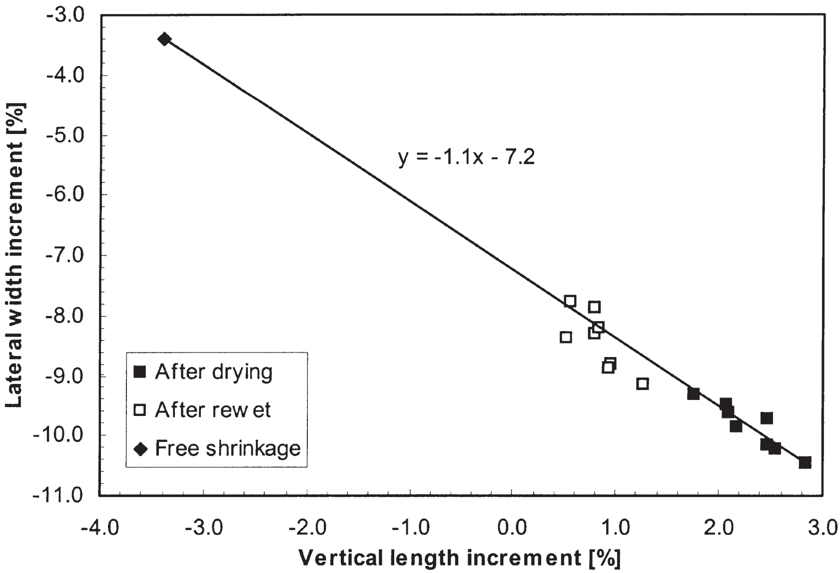


Figure 14 Vertical length and lateral width of samples after drying and after rewet.

Pilot machine results

At pilot machine it was not possible to measure elastic or plastic strain neither on-line nor off-line. Thus, breaking strain is used instead (measured in laboratory). It should decrease, if plastic draws increase during drying.

On the average, 1% wet strain decreases breaking strain 0.4% and increases tensile stiffness 56 kN/m. In comparison, the effect of the last draw at 91% dry solids content is small (1% draw decreases breaking strain 0.03% and increases tensile stiffness 8 kN/m). Thus, the results agree with the laboratory results.

Figure 15 compares breaking strain and tensile stiffness between the area of moisture streak and base paper. On the average, breaking strain is 1% smaller and tensile stiffness 3% larger in base paper than in the area of moisture streak. Apparently, this disagrees with the laboratory results before. If the draws are applied at larger dry solids content (base paper), plastic strain should be smaller. Thus, tensile stiffness should be smaller and breaking strain larger in base paper. However, the large drying range of the impingement unit (from 60% to 90% dry solids content) explains the results. If the moisture streak has larger plastic wet strain (and possibly larger plastic

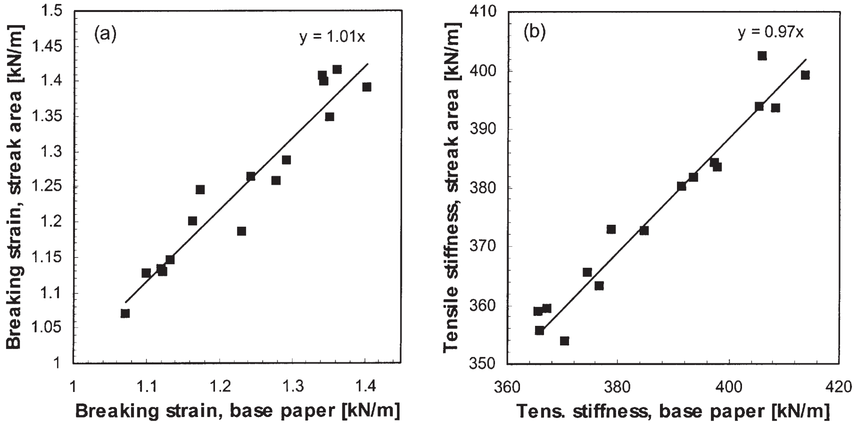


Figure 15 Breaking strain (a) and tensile stiffness (b) of the area of moisture streak vs. breaking strain and tensile stiffness of base paper in pilot drying machine.

relaxation), the streak area is not as tight as the base paper when paper web goes onto the drying cylinder below the impingement unit. Thus, the external drying tension is probably smaller at the most critical area of drying (Figure 11) and tensile stiffness of dry paper is smaller.

DISCUSSION

In this work the effect of moisture variation on cross direction MD tension profile is studied. Two principal parameters, elastic strain and tensile stiffness, are evaluated against different combinations of the draws during drying. In addition, relaxation and rewet properties of paper are briefly studied.

Elastic strain is relieved when paper specimen is unloaded. In opposite way, tension increases when elastic strain increases. The slope of the increase defines tensile stiffness. Thus, the product of elastic strain and tensile stiffness gives the tension level of paper specimen. Permanent length increment, i.e., plastic strain, occurs when strain level exceeds yield strain. Because tensile stiffness and strain components depend on dry solids content of paper, local fluctuations in moisture content induce tension variation.

The experiments show that tensile stiffness of dry paper increases most when paper is strained below about 70% dry solids content. This is due to the activation of fiber network, which up to some limit increases through plastic strain of paper [8]. Also, the draws between about 70–95% dry solids content increase tensile stiffness. It is conceivable that drying strain reduces the number of microcompressed [7] and wrapped-around [22] type bonding sites, when the collapse in fiber width occurs.

The amount of plastic strain is affected by two mechanisms. First, the proportion of plastic strain stretched in the draws decreases (and elastic strain increases) against increasing dry solids content of paper. Most of the plastic strain is drawn directly during straining and part of it is generated due to relaxation. The relaxation affects most in wet paper. Second, wet elastic strain is frozen as nonrecoverable dried-in strain of paper. This probably happens at the fiber collapse point [5].

The local variation of the moisture content of paper web affects the local rheological properties of paper. In addition, the initial variation of moisture content tends to increase along drying sections of paper machines. Therefore, the largest tension variation occurs between about 65–85% dry solids content, where both fiber shrinkage and moisture variation are largest. Between the same range the draws also increase most tension variation. The factorial model predicts that the tension variation of dry paper is about half of the worst case if the draws are avoided within this range.

The laboratory experiments indicate that the moisture induced tension variation of dry paper web is caused by elastic strain. On the average, the effect of drying history on the tension variation between the samples with different initial dry solids contents corresponds to the variation of the corresponding elastic strain. Tensile stiffness seems not to depend on small variations in the initial moisture content. On the other hand, the pilot trial does not confirm the laboratory results. However, this can be understood by the geometry of the drying pilot.

The discrepancy between the laboratory and pilot machine results shows that the whole drying history should be considered. In paper machine several consecutive draws follow each other and can have complicated interactions. For example, if in the first draw some part of the web has large plastic strain compared to the other parts, the same part could have small plastic strain compared to the other parts in the next draw, because the loose area must be tighten first.

The rewet experiments showed that part of the frozen dried-in strain of paper releases with water. The both rewet shrinkage in length direction and rewet expansion in width direction follow the trendline of the dried-in strain. It is interesting to note that the release of dried-in strains differs from typical observations on hygroexpansion at small water contents. Ordinarily, the strain release is not considered, although it has been reported that the minimum moisture content for the stress release is 8–10% [6]. This level can be well exceeded on surface layers of paper in different rewetting faces of coating and calendering processes. Thus, also the release of dried-in strains should be considered if one tries to control the tension profile of rewetted paper web. In addition, the dried-in strains probably affect rewet curl and cockling.

CONCLUSIONS

The results show that the tension variation of dry paper is generated by combined effect of moisture variation and straining during drying. Laboratory results indicate that tension variation is mainly caused by variation of elastic strain. Tensile stiffness, which is increased most by wet straining, does not vary much due to initial moisture variation.

During drying the largest tension variation occurs between about 65–85% dry solids content. In this area large draws should be avoided.

Part of elastic strain dries-in as frozen permanent strain. It can be recovered with a sufficient amount of water. The release of dried-in strain affects the properties of paper that relate to water addition.

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Transcription of Discussion

DRYING INDUCED TENSION VARIATION IN PAPER WEB

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Ilkka Kartovaara Stora Enso Oy

If you try to even out the moisture variations then you have two options; either dry the wet streaks or add water to the dry streaks. Based on your results, would you have a preference for either of these options?

Hannu Lätti

Of course if dry streaks occur before the drying section, then this is the best situation, but its not always possible to get that kind of situation. I think that nowadays power drying is the only way to get the moisture profile as flat as necessary, but in future, I hope that there will be some actuators in the drying section to correct the moisture profile in the correct places as early as possible in the drying section.

Tetsu Uesaka Paprican

Your conclusions seem to fit in well with what we have experienced in the mills. In the initial figure, you indicated that you applied in a wet state a different wet strength, and then achieved the different tension at the dry state, however you indicated that the final elastic strain still remained 0.2%. This is a very interesting result because 0.2% is a kind of magic number, which was indicated in past drying study histories, like Myat Htun, in this audience, and somehow 0.2% appeared over and over again in many drying studies, and even in your case, 0.2% still remained constant. Do you have any idea why this is so?

Hannu Lätti

No. I just studied one pulp mix – I have no right to say that this is the case in all cases, but it is very interesting to hear that you have got the same kind of results, that from different machines you get also 0.2%.

Tetsu Uesaka

Also 0.2% is very close to the yield strain that we normally see for the dry sheet, so somehow it is all inter-related without much explanation. It is a very interesting result.

Hannu Lätti

We intend to continue our studies when we get new equipment.