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THE EFFECT OF PRESS NIP GEOMETRY ON DRYNESS, DENSITY AND PAPER PROPERTIES

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INTRODUCTION

Efficient water removal in the press section has long been a key objective in paper production. A common rule of thumb is that a 1% increase in the dry content after pressing can result in a 4–6% reduction of the dryer demand. Increasing the web dryness after pressing is therefore extremely important for production efficiency. At the same time, pressing densifies the wet web which directly affects nearly every important paper property. An overly aggressive pressing strategy can destroy desirable paper properties such as bulk, deteriorate surface properties and printability, can create moisture variability that persists after drying and in extreme cases leads to web crushing. Despite several decades of research on the subject of wet pressing, there still remains many unanswered questions concerning an optimal press strategy for a given product quality.

Different pressing strategies are commonly used industrially, where the use of extended nip shoe presses has become more common. The specific pressing strategy has a large influence both on the web dryness after pressing, the web structure in the z-direction and on the final paper properties. The two general press profiles originate from the roll and shoe presses. The roll press is characterised by a short duration, high rate of compression and peak pressure pulse with a Gaussian-type profile. A shoe press is characterised by a long duration, low rate of compression and typically lower peak pressure, with the peak pressure occurring towards the end of the loading cycle. These press pulse profiles are shown in Figure 1.

In comparison to roll presses, shoe presses are known to result in a higher outgoing press dryness without overly densifying the web. This has justified their increased use industrially. The drawback with shoe presses is that tensile properties

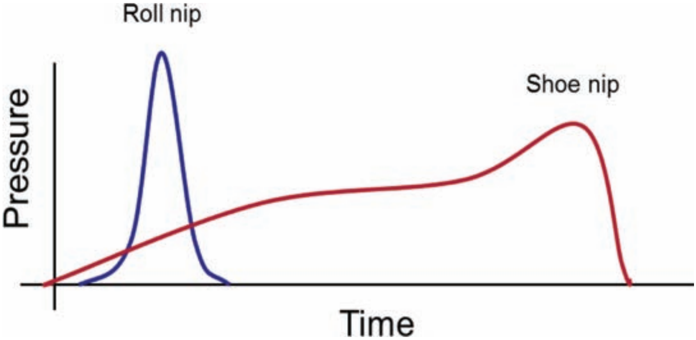

Figure 1. Characteristic pressure profiles for a roll and shoe press.

can be compromised. For the production of board grades, it is common to use a multi-nip press strategy consisting of a roll press nip followed by one or more shoe presses. Both roll and shoe press nips are believed to create density gradients in the web with the highest degree of densification on the side(s) of the web in in contact with the press felt, i.e. in relation to the direction(s) of water removal. In the case of the roll press nip, these gradients are believed to be more pronounced. However the extent of these density gradients are still poorly understood, particularly in relation to their impact on water removal efficiency and final paper properties; and even less so under industrially relevant conditions. A better understanding of the fundamental differences between roll and shoe presses is still needed in order to help tailor a specific press strategy based on product and production needs.

The aim of this work is to investigate rigorously the impact of roll vs shoe pressing on dryness, web structure in the thickness direction and paper properties under industrially relevant conditions. We do so through a series of pilot-scale production trials for an industrial 2-ply paper grade. The study focuses on board grades, where two of the most desirable physical properties are tensile strength and bending stiffness. The study has two main objectives, namely (1) to clarify the influence pressure profile (roll nip, extended nip) on achievable dryness, bulk and ZD density variation in relation to physical properties in the final product, (2) to determine the relationship between ZD-density profile, bending stiffness and tensile properties created by the different pressing strategies.

BACKGROUND

The wet web is extremely complex consisting of a quasi-random, compressible fibre network surrounded by water. The situation is complicated by the fact that water also resides inside the fibres lumen and walls, thus precluding more traditional descriptions of wet pressing as flow through porous media. Despite these complexities, simple models of pressing have given valuable insight into some of the dryness benefits observed with extended nip shoe presses. Carlsson *et al.* [1] were perhaps the first to provide insight into the advantages of shoe presses by considering the web as a visco-elastic material. In their studies, they found that maximum solids content in the web could be observed at later stages of the press pulse and not coincident with the peak of the pressure profile. Moreover, the point of maximum web dryness was found to shift further towards the end of the press cycle as the level of fibre beating was increased. With these observations, they described the wet web as a visco-elastic material consisting of one viscous component with viscosity μ and one elastic component with compressive modulus E, connected in parallel, i.e. the so-called Kelvin element model. They refer to the viscous and compressive components as flow controlled and compression controlled components respectively. When the dewatering is completely compression controlled, the maximum solids content occurs when the web is subjected to the maximum pressure, and when the dewatering is completely flow-controlled, the maximum solids occurs at the end of the press pulse. Carlsson *et al.* [1] showed that this delay time increases with beating/refining level and is generally much longer for chemical pulps compared with mechanical pulps. Using this description, the authors were then able to model the average time dependant thickness of the web for a given press profile, characterized by a time constant for the deformation of the Kelvin element, referred to as the "retardation time". The ratio between this retardation time for the wet web and the duration of the process is a dimensionless number called the Deborah number [2], DEB:

$$DEB = \frac{time\ of\ retardation\,(\tau)}{duration\ of\ the\ process\,(t)} \tag{1}$$

Compression-controlled nips are thus characterized by a Deborah pressing number <<1 and flow-controlled nips by a Deborah pressing number >>1. During pressing, the Deborah number increases from values less than one to values greater than one. Hence, it is expected that the dewatering behaviour of the web becomes more flow-controlled at higher solids content. This result has also been supported by direct experimental evidence [1].

The water contained inside the fibre wall creates a great challenge for pressing. The role of fibre swelling in wet pressing was first explored by Carlsson *et al.* [3] using a methodology akin to solute exclusion, by following the dilution of high molecular polymers during water removal. They showed that the first water to be squeezed out during pressing is the water between the fibres. As soon as the water in between the fibres has been squeezed out, the cell wall water begins to be squeezed out. Further, the higher the swelling of the fibre the lower is the press solids content. Some years later Busker (e.g. [4]) in practical experiments on paper machines confirmed the role of swelling in water removal during pressing predicted by Carlsson *et al.* [3].

Wet pressing is complicated further by the non-uniform deformation response of the web. More specifically, as water is removed, the web is compressed and undergoes changes in the geometry of the porous medium along with its resistance to flow, e.g. [5]. After pressing, the web is able to recover some of its pre-pressed structure. The fibres are also known to twist and collapse during pressing [6] which affects the web permeability. These structural changes are dynamic in nature and have significant effect on water removal efficiency. In the absence of interstitial water, the flow of water through an idealized wet web could be described using traditional theories for flow through porous media, namely the Kozeny-Karman model ([5], [7]). With this model the water velocity within the web, v, is modelled mathematically as,

$$v = \frac{K}{\mu}\frac{\partial P_H}{\partial z} \tag{2}$$

$$K = \frac{C\,\phi^3}{r\,(1-\phi)^2} \tag{3}$$

where μ is the water viscosity, K is the web permeability, φ is the volume fraction available to flow, r is a characteristic network pore radius, C is material constant, and P_H is the hydraulic pressure in the web. However, as the web densifies in the thickness direction, the web permeability K, and volume fraction φ vary dynamically in the thickness direction, z. Moreover, these parameters depend non-linearly on the fluid velocity, v. One of the earliest and simplest model descriptions for this non-linear relationship between the web structure in the thickness direction and the fluid velocity can be described with Terzaghis principle [8], which states that the total pressure exerted on the web, P_T is equal to the hydraulic pressure inside the web, P_H and the structural pressure taken up by the web network, P_S, i.e.

$$P_T = P_H + P_S \tag{4}$$

This principle is illustrated in Figure 2. Terzaghi's principle states that the structural stress taken up by the web must counter the hydraulic pressure driving fluid through the web. Since the lowest hydraulic pressure occurs on the felt side where water is removed, the structural stress within the web must be highest on the water removal side, i.e. the web densifies in this region. As a result, a

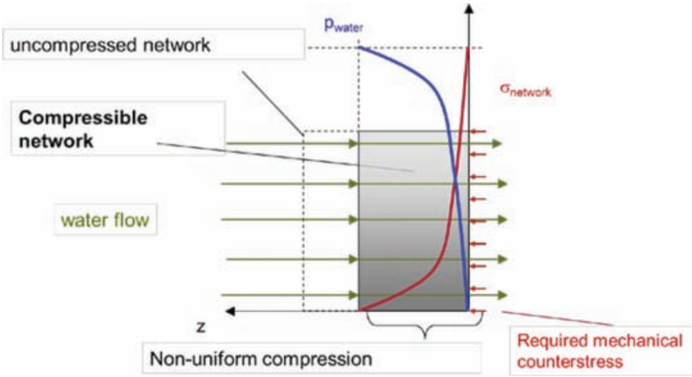

Figure 2. Schematic description of Terzaghi's principal applied to wet pressing. In this figure, the thickness direction and water flow is from left to right and the web is depicted as the grey shaded region.

non-uniform hydraulic pressure gradient in the web leads to non-uniform densification profiles within the web. This phenomenon has been observed by many researchers, e.g. [9], [10], [11] and [12].

Evidence of non-uniform web densification was shown in studies by Szikla *et al.* [13], [12]. Using fast, one-sided water removal with a roll-type press pulse, a large density gradient was observed across the entire thickness of the web. In studying micro-striations on the paper surface, MacGregor and Conners [11] hypothesized density gradients as an underlying cause. However, MacGregor and Conners were unable to find such gradients shown by Szikla and instead postulated the existence of only a very thinly densified region near the web surface which they refer to as dense 'skin'. They further argued that this densified layer of fibres on the web surface cause an immediate build-up of flow resistance in these layers, which in turn results in further surface densification. This hypothesis was supported in part by Burton [10], who studied the effects of flow resistance (freeness) and moisture ratio on density development during the wet pressing of handsheets. Using a dynamic thickness measurement system inside the web, Burton showed a non-uniformly densification occurs in the web with the highest degree of densification occurring on the side of the web in contact felt. The phenomenon was shown to be far more profound with low freeness pulps and was accredited to the flow controlled nature of low freeness pulps. Such strong density gradients shown by Szikla and Burton have not been observed under industrial pressing conditions (at least to the knowledge of the authors).

The effect of pressing on basic sheet properties

A well-known effect of wet pressing is to densify the web which is critical to almost every strength property in paper ([14], [5]). Strength properties, e.g. tensile, z-strength, SCT, burst, etc. typically increase linearly with density, regardless of fibre type and/or press profile, although the slope of this linear relationship can vary depending on these parameters. However bending stiffness, *B*, one of the most important properties for most board grades, is in general adversely affected by an increase in density due to its non-linear dependence on thickness, i.e.

$$B = \frac{Et^3}{12} \tag{5}$$

where *E* is the material tensile stiffness and *t* the web thickness. In order to improve the bending stiffness for a given grammage, it would therefore be most advantageous to reduce the density thereby increasing the thickness. However, many have argued that bending stiffness could be optimized with a dense, stiff outer layer to increase the tensile stiffness in these regions while maintaining a bulky, low density core, i.e. the so-called I-Beam construction. Considering the known densification effects associated with roll press nips, an optimal combination of shoe and roll pressing might be beneficial in this regard. This motivates a better understanding of the potential for creating an I-Beam structure by creating an optimal a density variation in the web thickness direction choice of press strategies.

In the first part of the work we explore dryness-density relationships for roll and shoe-type press nips and relate these results to theoretical reasoning found in the literature. We then explore the effect of these press configurations on product properties, with particular focus on bending stiffness and tensile properties. In the last part, we study the web structure in the thickness direction and correlate this to dryness and paper properties realized with the different press strategies.

EXPERIMENTAL PROGRAM

The experimental program is based on a series of pilot scale production trials performed on the FEX paper machine at the RISE Bioeconomy research institute in Stockholm. A two-ply board grade, 116 gsm, was produced consisting of unbleached softwood kraft pulp (UBSK) in each ply beaten to 22 °SR. Although not a highly beaten, UBSK is representative of a flow controlled fibre. No other additives or filler were used. The first ply, 56 gsm, was formed in a pure roll former configuration using a low contraction, KMW 3-layer headbox (5 rows × 11/10 tubes per row), with slice opening 12 mm. The second ply, 60 gsm, was formed in a Fourdrinier configuration using a Valmet headbox (7 rows × 11 tubes per row) with slice opening 12 mm. The two plies were then couched together prior to entering the press section at approximately 19% solids content. The machine speed in both forming sections was 600 m/min and samples were collected at the jet-wire speed ratio yielding the minimum fibre orientation anisotropy. The webs were then free-dried in a 10-cylinder dryer unit.

Pressing

The press section for these studies consisted of 3 press nips, see Figure 3. The first press nip is a traditional roll press. The second press nip is a single felted, extended nip shoe configuration with both the shoe and felt positioned underneath the web. The third press nip is also a single felted, extended nip configuration with both the shoe and felt positioned above the web. In these trials, the first roll nip press load was held constant at 20 kN/m. This nip was used only to prevent web breaks prior to the 2nd and 3rd press nips and did not affect the web structure prior to subsequent pressing. The second nip was a traditional extended nip shoe press, with linear loads considered of 100, 500 and 1000 kN/m.

Roll and shoe pressing were simulated using two different shoe geometries in the 3rd press nip. A specially made convex shoe (nip length *ca*. 25 mm) allowed simulation of a traditional roll press and a standard concave shoe press (nip length *ca*. 260 mm) was used for shoe pressing. Both nip types were equipped with a series of pressure sensors allowing the possibility to measure the press profiles for the different press geometries. The linear loads considered in the third press (second shoe nip) were 100, 500 and 1000 kN/m for the conventional, concave

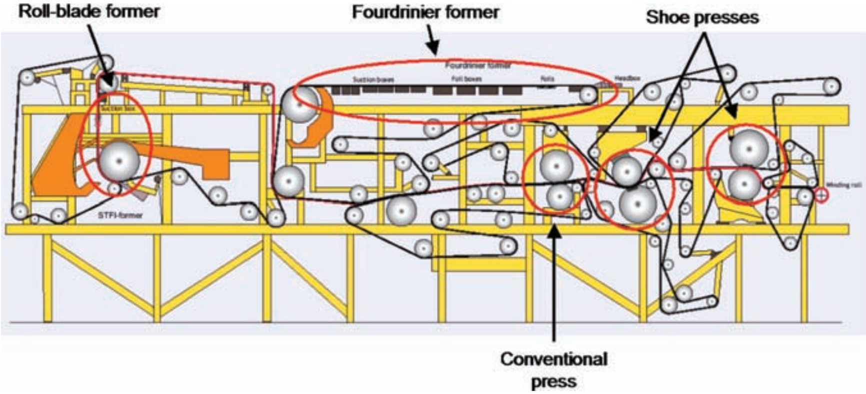

Figure 3. The FEX pilot-scale research paper machine.

shoe nip and 50, 150 and 250 kN/m for the simulated roll nip. A summary of all trail points studied are given in Table 1. Example press profiles for the two nips are shown in Figure 4. The solid curves in this figure are polynomial fits to the pressure measured within each nip.

Table 1. Summary of the different press configurations and loads

Trial	*2nd Nip*		*3rd Nip*	
	Press Concept	*Linear Load* [kN/m]	*Press Concept*	*Linear Load* [kN/m]
1	Shoe	100	Shoe	100
2	Shoe	500	Shoe	100
3	Shoe	1000	Shoe	100
4	Shoe	100	Shoe	500
5	Shoe	500	Shoe	500
6	Shoe	1000	Shoe	500
7	Shoe	100	Shoe	1000
8	Shoe	500	Shoe	1000
9	Shoe	1000	Shoe	1000
10	Shoe	100	Roll	50
11	Shoe	500	Roll	50
12	Shoe	1000	Roll	50
13	Shoe	100	Roll	150
14	Shoe	500	Roll	150
15	Shoe	1000	Roll	150
16	Shoe	100	Roll	250
17	Shoe	500	Roll	250
18	Shoe	1000	Roll	250

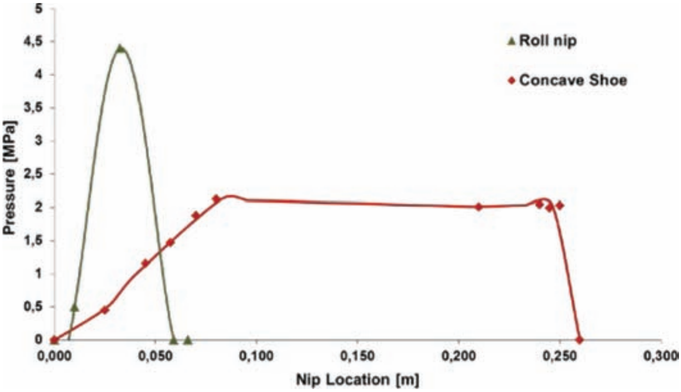

Figure 4. Example press profiles for the roll and shoe nips. The solid lines are polynomial fits to the pressure measurements within the nips.

Evaluation and analysis

For each trial point the press dryness before and after each nip was measured. The grammage for each sample was measured according to ISO 536:2012; the structural thickness and density were measured according to SCAN-P 88:01[1]. Physical properties were also measured for each trial point, including tensile properties (ISO1924-3:2011), bending stiffness (ISO 2493), and Bendtsen surface smoothness (ISO 8791-2:2013). All mechanical properties are expressed as the geometric mean, i.e. the square root of the MD and CD values.

Fines content and fibre morphology was measured in select samples produced with the different press strategies by first re-slushing dried samples and then measuring the fibre length distributions using the L&W FiberTester. No significant difference was observed in fines content or fibre morphology within any of the samples.

The density profiles in the thickness direction were also measured for two select trial points for the shoe and roll press nips using CT tomography. An Xradia MicroXCT-200 was used to capture 3D images, and for this study images of approximately 1 mm × 1mm × 1 mm with a pixel size of 0.9 μm were collected. The method for acquisition and analysis is well described in detail by [15]. The image of each sample was analysed for the fibre/non-fibre share in 50 zones in z-direction. Each zone is in this case approximately 3.5 μm. The shape of the zones is flexible, i.e. the zones are defined starting from the surface of the sample and towards the centre. The surfaces of the sample is defined using a running mean filter on the vector of the surface pixels of a segmented image, where the smaller the filter window, the denser the surface zone becomes. The size of the filter window was in this case 17 pixels, and this gives a surface closely following the outer edge of the sample, but it will include some surface pores. The analysis was made in 2D cross-sections (*ca.* 950) of each 3D image, and the average was computed. To capture the variability over the sheet, density profile measurements were made on 8 different sample points over an A4 sheet for each trial point.

RESULTS

Effect of press configuration on dryness and density

For most paper grades, the press dryness and density of the final product are of the most important properties. It is therefore instructive to consider first the density-dryness relationship for both press concepts, see Figure 5. Shoe pressing resulted in significant improvements to the density-dryness relationship, where the shoe press resulted a much lower density for a given dryness, something which is advantageous for improving bending stiffness. Analogously, the shoe press can be said to achieve a much higher web dryness for a given density. The fact that the shoe press geometries improve the density-dryness relationship is well known and is one of the key reasons supporting their increased use industrially. The improved dryness observed with the extended shoe nip press is partially supported by the theories of [1]. Specifically, the long nip residence time of the shoe press strategy allows the time-dependent, viscous component of the web to respond to the press pulse. However, considering the lower rate of densification with respect to dryness, it could also be argued that the shoe press results in a more open, porous web structure with a higher permeability to flow thereby allowing a more efficient dewatering. That is, the shoe press results in a more compression controlled response, despite higher web dryness.

In [11] it is suggested that the low dryness observed with roll press nips is due to the creation of a thin, densified layer on the web surface in contact with the press felt, i.e. in the direction of water removal. This very thin, highly densified layer would result from the very short but intense application of pressure associated with roll pressing, causing the structural pressure of the web to increase rapidly at the web surface. This densification, albeit very thin according to [11], would then reduce the web permeability at the surface and restrict water removal, i.e. resulting in flow-controlled behaviour in the densified region, accompanied by a compression controlled behaviour in the middle part of the web. Investigation of the surface roughness can be used to support this hypothesis, where a smoother surface is expected to correlate to a more densified web. Figure 6 shows the Bendtsen surface roughness as a function of density for the two press configurations. Here it can be seen that the surface roughness corresponding to the shoe nip is significantly higher than that of the roll nip, i.e. yielding higher Bendtsen values. The fact that Bendtsen values obtained from the roll and shoe press do not follow

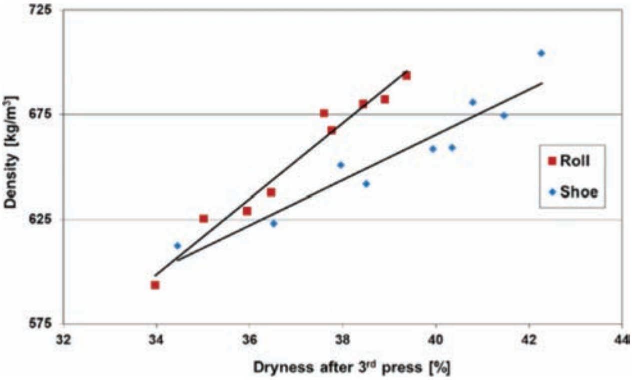

Figure 5. Density as a function of dryness for the different press concepts

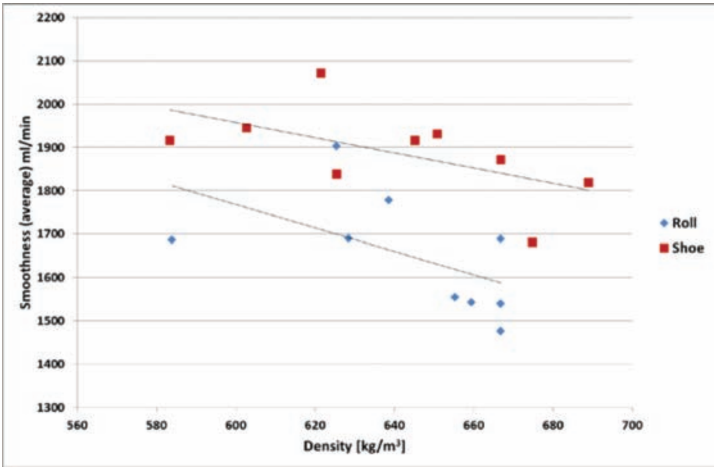

Figure 6. Bendtsen surface roughness as a function of dryness for the different pressing concepts.

a single relationship with respect to density would suggest that the web has densified non-uniformly, and possibly 'sealed' at its surface with the roll press strategy, creating a very low permeability locally which has restricted water removal.

Press configuration and mechanical properties

As this study is oriented towards board grades, the effect of the press configuration on bending stiffness and tensile properties is studied in more detail. One particular challenge with board grades relates to maintaining tensile properties at a high bending stiffness and low density. Figure 7 shows a plot of the bending stiffness index (geometric mean) vs press dryness for the different press strategies. In general, the bending stiffness is found to decrease with an increased dryness, a result which is associated with the increase in density accompanying an increase in press dryness.

The shoe press can be seen to result in a significant increase in bending stiffness for a given dryness. This result is reflected in Figure 5, where the shoe press strategy results in a lower density at a given dryness. However, we feel that a better way of interpreting this plot is that the shoe press results in a significant dryness increase at a specific bending stiffness. That is, both press strategies are able to achieve a given bending stiffness, however the shoe press does so at a higher dryness.

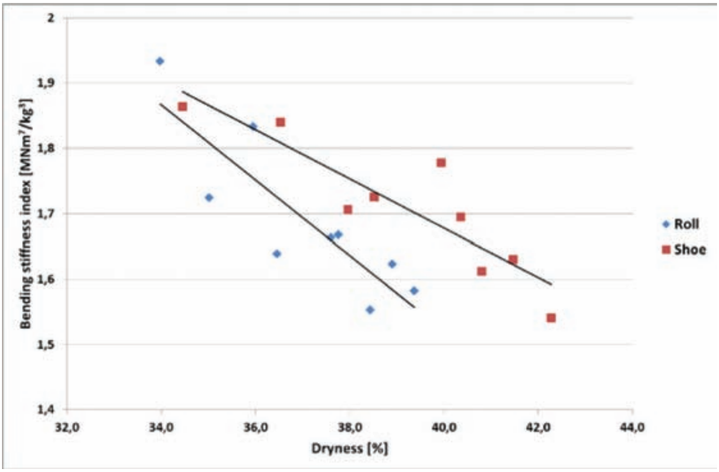

Figure 7. Bending stiffness as a function of dryness for the different press concepts.

As given in Equation 5, the bending stiffness depends primarily on the web thickness, but also on the modulus to a lower order of magnitude. In order to elucidate the influence of these two parameters on bending stiffness for the different press strategies, we plot the bending stiffness as a function of the web thickness, see Figure 8, and the tensile stiffness index, see Figure 9. Figure 8

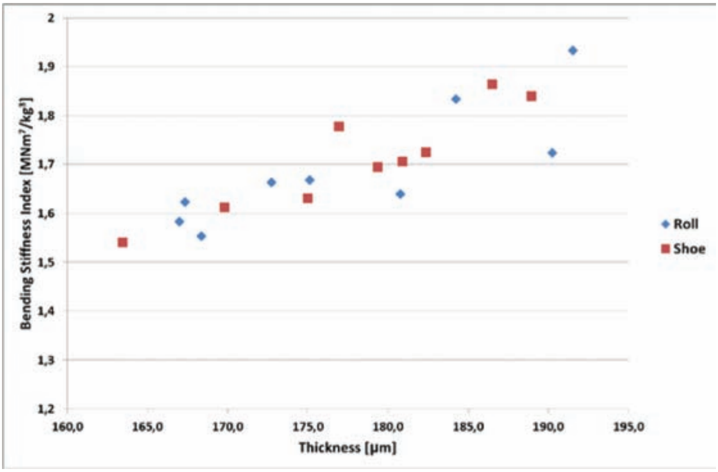

Figure 8. Bending stiffness index vs web thickness for the different press strategies.

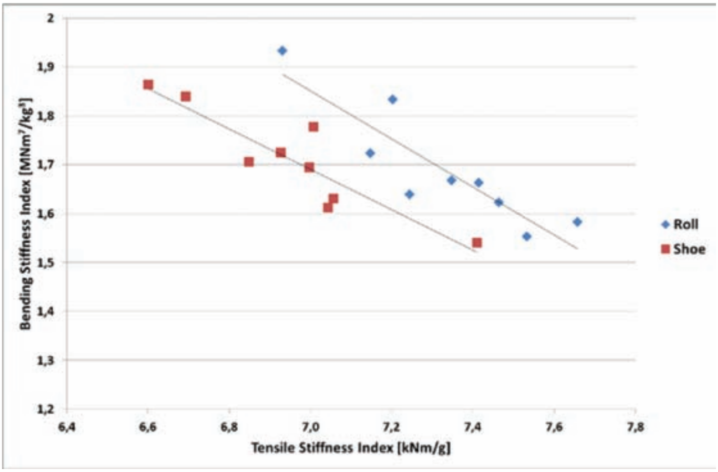

Figure 9. Bending stiffness index vs tensile stiffness index for the different press strategies.

shows that the dependence of bending stiffness on thickness is independent of the press strategy, i.e. the bending stiffness – thickness relationship falls on a single line. However, Figure 9 shows a shift in the bending stiffness – tensile modulus relationship towards higher values with the roll press strategy. This shows that it is possible to recover a significant amount of bending stiffness at a higher density with the roll press through an increase in the tensile modulus, although at a significantly lower dryness.

Before investigating the tensile properties resulting for the different press strategies, it is instructive to consider the relationship between tensile strength and tensile modulus. Figure 10 shows that the tensile strength dependence on modulus falls on a single curve, which is in agreement with the results of Page and Seth [16]. However, the roll press strategy has resulted significantly larger tensile values along this curve.

It was shown previously that the roll press strategy resulted in improvements to the bending stiffness – tensile modulus relationship, while both press strategies resulted in essentially the same dependence on thickness. It is therefore of interest to investigate differences in the tensile stiffness index for the two press strategies, see Figure 11. Here it can be seen that the roll press results in a significant improvement to tensile stiffness for a given density in comparison to the shoe press. This again suggests an effect of a non-uniform web densification achieved with the roll press, where a highly densified region on the surface is able to improve the tensile modulus despite a common average density. Similarly, the

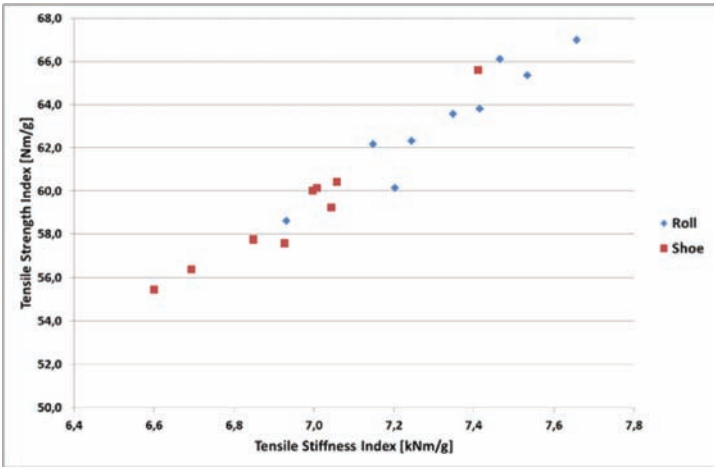

Figure 10. Tensile strength as a function of tensile stiffness for the different press strategies.

shoe pressed webs are of lower density and with a higher porosity, which improves bulk and dryness but with a reduced tensile stiffness.

It is of interest to plot the bending stiffness index vs tensile strength index for the different press concepts, see Figure 12. Here it can be seen that the bending stiffness decreases almost linearly as the tensile strength increases for the low and medium press loads (higher bending stiffness values), but the rate of decrease in

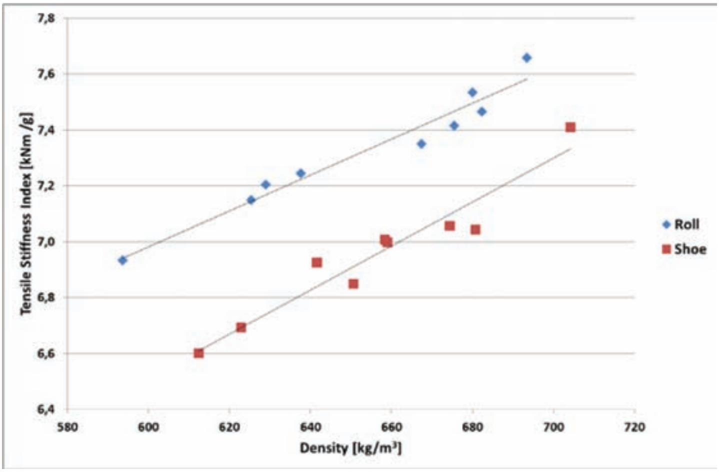

Figure 11. Tensile stiffness index as a function of density for the different press strategies.

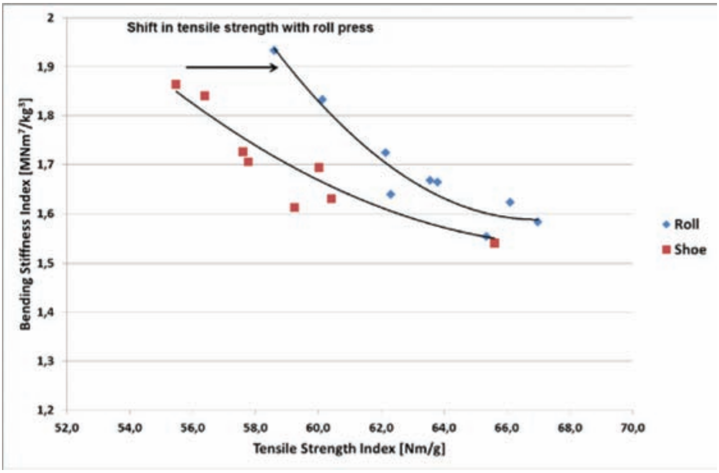

Figure 12. Bending stiffness index vs tensile strength index.

bending stiffness with respect to tensile strength is slightly greater for the roll press strategy. To reiterate, this is due to the increase in density as the press load is increased, i.e. tensile strength increases and bending stiffness decreases. However with the roll press strategy in the 3rd nip, the tensile strength is seen to improve significantly. At the higher press loads, the bending stiffness appears to no longer decrease linearly, perhaps indicating a minimum thickness/maximum density is being reached. The improvement in tensile strength index with the roll press is also found to become less significant at the lowest bending stiffness cases, however improvements are still notable.

Effect of press strategy on ZD web structure

In order to study structural changes in the web created by the roll and shoe press strategies in more detail, the density profiles in the thickness direction were measured for two select trial points, namely for the press strategy consisting a first shoe nip, 100 kN/m (2^{nd} nip) followed by a roll nip, 50 kN/m (3^{rd} nip), i.e. trial point 10 in Table 1, and for a shoe nip, 100 kN/m (2^{nd} nip) followed by another shoe nip, 100 kN/m (3^{rd} nip), i.e. trial point 1 in Table 1. These two points were chosen as those yielding the highest bending stiffness (approximately identical in each case) but with a significant improvement in tensile strength index with the roll press. These trial points are those in the uppermost left hand corner of bending stiffness-tensile strength index plots shown in Figure 12. The average density profiles for these two trial points are shown in Figure 13, where the bottom part of these profiles (0 μm in thickness direction) corresponds to the side of the web in contact with the press felt in the 3rd nip, i.e. where the press strategy was varied. It should be noted that the sharp, upward parts of the density curves at the web surfaces, i.e. those regions lying outside of the dashed lines in Figure 13, are due to the inherent difficulties in defining and interpreting the uneven web surface. The definition of the web surface in the image analysis algorithm, in its strictest form, gives a 100% fibre share on the surface. This definition however gives a very uneven surface of the web, and cannot be defined as the even, well defined surface one typically perceives. And since there is no known single definition of the surface over the entire sample, it is here defined using the filtering method described earlier in a way such that surface pores are also included in the definition of the surface. In this case the smoothing filter can give up to 50% fibre share on the surface.

Away from the outer regions near the web surface, it is difficult to draw any general conclusions on differences in the average density profiles obtained from the roll and shoe presses. Although it could be argued the roll press nip has produced a slightly greater density gradient on the corresponding web side, the variability between measurements in the main parts of each sample (shown in Figure 14) is so large that any differences in density gradient are not believed to be significant. Moreover, we do not see the extreme density gradients shown previously by [13] and [12].

Figure 14 shows the average density profiles for each of the 8 samples from the roll and shoe press strategies. There is clearly a large degree of variability in the

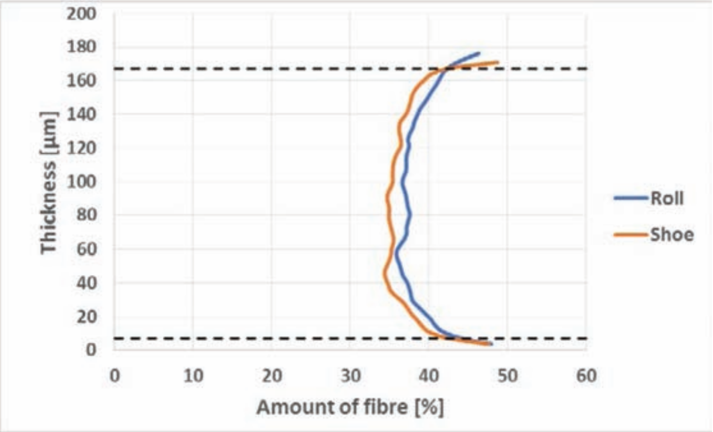

Figure 13. Average density profiles in the thickness direction measured using CT tomography for the roll and shoe press strategies.

measurements made on the different sample points, particularly for the shoe press. These profiles also highlight the difficulty of measuring the density at the web surface, where the filtering method might interpret an increasing or decreasing density gradient at the web surface depending on the number of pores found on the so-defined web 'surface'. For the roll press however, the density gradient is found to increase rapidly on the surface of the web corresponding to the side of dewatering in this nip for all 8 measurements, i.e. along the 0 µm (bottom) surface and at approximately the same rate. Further, the point where this sharp density gradient occurs is approximately the same in all but one of the measured profiles, namely at *ca*. 15 µm, as is the density gradient. Although this is not necessarily a 100% conclusive measurement, we believe this observed trend gives a good indication of both the thickness and sharpness of web densification created by the roll press strategy. In comparison, the density profiles measured from the shoe pressed samples can be seen to either increase or decrease on this same side of the web, something which is connected to the more porous web structure created by the shoe press profile.

Visual inspection of cross sections of the webs corresponding to each press strategy also shows very different web structures for the different press strategies. Figure 15 shows example cross sectional tomography images corresponding to the roll and shoe press strategies, where the lower web-side in these images corresponds to that in contact with the press felt in the final nip, i.e. where the press strategy was varied. Careful inspection of the bottom side of the roll pressed sample (shown left) shows a highly densified layer on the web surface, approximately 15 µm in thickness, i.e. on the same order of magnitude as the measured profiles shown in Figure 14. The densified region observed here is significantly

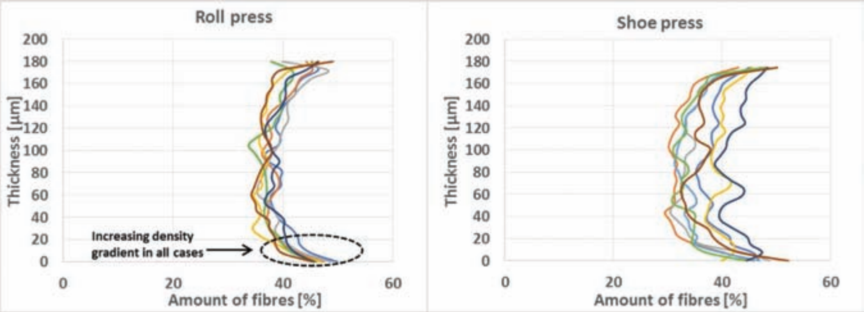

Figure 14. Average density profiles in the thickness direction for each independent measurement point. The density profiles on the left are for the roll press and those on the right are for the shoe press.

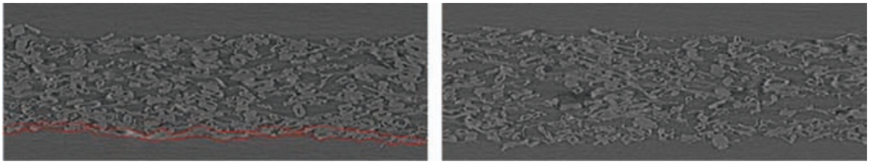

Figure 15. Example cross sectional tomography images from samples pressed with the roll nip (left) and the shoe nip (right).

thicker than that previously reported in [9], who first showed a 'barely discernible' skin of approximately 1–2 μm in thickness, detected through scanning electron microscopy.

The cross-sectional web image corresponding to the shoe press strategy shows a very different structure. Here, there is no discernible surface densification and, in general, the web can be seen to be far more open and porous in structure, particularly at the surface. The tomography image for the shoe pressed web would support the argument that shoe pressing results in a more porous web structure through which water can flow freely, thereby improving the press dryness significantly.

DISCUSSION

The results presented here give a detailed analysis of the influence of press strategy on the web structure in the thickness direction and its effect on bending stiffness and tensile properties. The shoe press resulted in significantly lower densities for a given press dryness and without observable density gradients in the thickness direction. This correspondingly resulted in a higher bending stiffness for a given dryness. The roll press nips were observed to result in a thin but significant densification on the web side in contact with the press felt. The extreme density gradients presented by other research groups have not been observed in these trials. Rather, we observe a densification closer to the surface skin concept proposed by [9] but of an order of magnitude greater in thickness.

The results support the theory of MacGregor and his predecessors in relation to the known dryness benefits associated with shoe presses. More specifically, with roll pressing, the web densifies rapidly on the surface in contact with the press felt which creates a reduction in the web permeability, or a 'sealing' effect, that inhibits efficient water removal. This surface densification can be related to the flow-controlled vs. compression-controlled concept proposed by [1] and later supported by [10]. However, this concept must be considered locally in the web thickness direction rather than an average behaviour in the web thickness direction.

More specifically, the large peak pressure and high initial rate of compression of the roll press creates a strong densification on the outer layer of the webs. This results in a flow-controlled region on the outer layer of the web but a compression-controlled region in the inner region of the web. The shoe press on the other hand has a low initial rate of compression, lower peak pressure and longer nip residence time. The low initial rate of compression and peak load does not densify nor seal the web surface, but maintains a more open and porous web structure through which water can more easily be removed. Moreover, the longer nip residence time of the shoe press provides the time needed for viscous component of the web to respond, thereby yielding improved press dryness.

The roll press was able to achieve similar bending stiffness values as the shoe press but at significantly lower press dryness. The roll press did however result in significant improvements to tensile properties at approximately equal average densities to those of the shoe press. This is partly believed to be a result of the non-uniform densification in the thickness direction, whereby the densified surface created by the roll press results in improved tensile properties. However, the non-uniform densification alone is not enough to account for the improvements in tensile properties observed here. To support this claim, we present a very simple estimate of the effect of the non-uniform densification on strength improvements as follows. We first assume 10% of the roll pressed webs have densified by approximately 25%, numbers which are based on the data presented in Figure 14. Given that the fibre type, morphology, refining level and fines content were identical for the different press strategies, and considering that we have analysed the geometric mean of properties, thereby eliminating the effect fibre orientation, we very generally assume that the tensile stiffness is proportional to the web density. In reality the tensile stiffness is a more complicated function dependant in particular on the relative bonded area [16]. Using the simple assumption that tensile stiffness is proportional to density, we would estimate improvements due to non-uniform densification on the order of 2.5%, far lower than the improvements observed here with the roll press. It would therefore appear that the relative bonded area in this densified region must have been increased in a way not captured by density alone.

CONCLUSION

A series of pilot-scale production trials have been performed to investigate the effect of press strategy on dryness, density gradients in the thickness direction and paper properties for an industrial 2-ply paper grade. It was of particularly interest to determine if the bending stiffness and tensile strength could be improved by optimizing the press strategy that would result in a stiff outer layer and a bulky middle layer. The press strategies studied here involved a two-nip concept, where the second nip was varied as either an extended nip shoe press or short duration roll press. The first nip was a conventional, extended nip shoe in all cases. It was shown that the shoe press strategy resulted significant improvements in web dryness and that this was due to creating a more open, porous web structure through which water is removed more efficiently. The roll press strategy appeared to create a highly densified region on the side of water removal, which sealed the web surface inhibiting water removal. For a given web dryness, the shoe press strategy was shown to result in a lower density web with a higher bending stiffness. At a lower press dryness, the roll press strategy was shown to result in bending stiffness values comparable to the shoe press but able with significant improvements to tensile properties at equal average densities to the shoe pressed webs. The increase surface densification alone was not enough to account for these improvements in tensile properties.

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Transcription of Discussion

THE EFFECT OF PRESS NIP GEOMETRY ON DRYNESS, DENSITY AND PAPER PROPERTIES

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Joel Panek WestRock

To summarize this: You are seeing a relationship where the normalized bending stiffness is the same for both, but then you are seeing a difference in the tensile properties, so it is solving the mystery of what is driving that difference.

Torbjörn Wahlström Stora Enso

This has been a great attempt to answer the old question of whether there is a gradient or not in roll versus shoe pressing. But, if you get the gradient here and it affects the tensile stiffness index, why does it not affect the bending stiffness index?

Paul Krochak RISE Bioeconomy/Papermaking and Packaging

Yes and it's a good question. I have gone back and forth putting this together and thinking about it and what the heck does this all mean. It is easy to say that at least with pressing, increasing the tensile stiffness is not going to contribute that much. Of course, it is a different story with multi-ply products when you actually have 60 g or whatever on the outer plies that can contribute. However my conclusion is that at least trying to create the structure and pressing this ideal bending stiffness, I-beam structure and pressing, and focusing on the thickness and not on increasing the tensile stiffness. Remember this is multi-ply with two plies with the same grammage so it is not a typical board construction.

Discussion

Jean-Claude Roux Grenoble University

I have one question regarding the value of the engineering parameters. On the global view, can you compare the average mechanical total pressure between the both cases, roll and shoe press, because it could to a certain extent explain the gradient density you are looking for?

Paul Krochak

I was wondering if somebody would ask that. Yes, you can, but of course that is another piece of work which is not here. It's a little bit of a longer discussion but if I understand your question correctly, let me try and summarize it like this. I think that the global parameters are the initial rate of compression at the nip length and the peak pressure. So, for a shoe press we have this very nice density–dryness relationship. This slope is driven by the initial rate of compression and a lack of peak load. So that's exactly what we had, low rate of compression, no peak; it was almost a square. A roll press, on the other hand, has a very high peak load and the peak load is what drives this gradient. The dryness, you could have the same peak load if you put it very early, or very late, so now we have to come into specific profile. If it is very early, your dryness will be out here, which is not so desirable. No one would be happy with these kinds of dryness. If you put it very late, you can shift this whole curve out in this direction, same slope. Again, these results which are not presented and this is an entire different presentation, but I hope that answers your question.

Jean-Claude Roux

Yes. I also agree with you. Under this scheme we can see the slope is to a certain extent responsible for an open structure, or a closed structure. I mean the gradient density is close to the water extraction.

Georg Goetz, SIG Combibloc

What would be the effect of the pressing strategy on Scott bond or ZD-tensile values?

Paul Krochak

Yes. ZD-tensile would be very similar to tensile strength. I actually have those, and Scott bond would also be very similar. I don't know if I have them in this study, but we have done similar studies and measured it. We like that strength, but we have done Scott bond too and it is very similar to tensile strength, very similar to the ZD-tensile. You get an increase with the roll, or a roll-type nip and of course your dryness, but more or less in all of those strength curves you can replace your favorite density dependent property.

Peter de Clerck PaperTec Solutions Pte Ltd

Looking at the results there is some similarity to the calendering of coated board in respect to surface densification. Much board was produced with a BCTMP under layer and a bleached kraft top layer than coating on top. When the board is calendered hard you will often see a gloss mottle corresponding with the formation of the less-compressible BCTMP under layer, i.e. there is selective densification of the top layer depending on the compressibility of the under layer. You might be seeing similar selective densification in your pressing work, resulting in this surface layer effect?

Paul Krochak

Absolutely, but the only thing with this is that we use a 100% unbleached sulphite kraft, so in principle, it is all the same fibre.

Peter de Clerck

Yes, but the fines and the degree of fibrillation also give different compressive strengths with the elements composed.

Paul Krochak

Yes. That's a good point and we have thought about this.

James De Witt SAPPI

In terms of getting at the surface densification, did you do oil Cobb tests? This test can be useful in differentiating surface permeability, which is a function of surface compaction.

Paul Krochak

No, we didn't. Maybe, it could be interesting.

Discussion

Fredrik Lundell KTH Royal Institute of Stockholm

Thanks for a very nice presentation. I've been staring at your spaghetti lines for a limited time and I am starting to see things. The shoe press data seem to indicate fairly large variations in the density in the center of the sheet. Is this a true feature of the data? Can you comment on this?

Paul Krochak

This is what made us stare at these spaghetti lines for so long. You can see it's very open, so again this comes back to this, do you count the fibre or do you count the pores? So this is actually very common when we do this with shoe pressing because of this pore structure it tends to be very noisy because there are a lot of pores.

Jean Francis Bloch Grenoble University

We published some time ago results of X-ray measurement dedicated to the structure and plotted porosity versus thickness. Usually the external structure is more porous, I will say it corresponds to what you call roughness: it is more porous; then it's constant in the bulk. Here you show that it's more dense on the surface due to the densification caused by pressing. But if you are looking to the other side, it is also more dense there and I do not understand this result.

Paul Krochak

Yes, but this is the thing, it tends to be more dense up because it is how you define the surface. This is an issue with this algorithm, but if you see for example, sometimes it goes up and sometimes it goes down.

Jean Francis Bloch

So it is an artefact of your method? The problem is that you find results exactly, using this method, and you are going to draw conclusions on both sides. So the results are due to your method or is there really a density gradient?

Paul Krochak

It is an inherent issue with the method, the method and the web itself. So the method is correct. It sees what is sees, but what it sees . . .

Jean Francis Bloch

No. No. No. You will have always results from your method. Producing results does not mean that they are correct. But didn't you extract water on the second press in the opposite direction than in the first one?

Paul Krochak

Yes, exactly, and this is what I tried to be very clear of, so we were very, very meticulous. We mark our samples, so we know keep track of the sides. We were very, very careful.

Jean Francis Bloch

And that was exactly the point I wanted to make, because usually if you want to have a constant profile of porosity it is just impossible. You know that. You have to have a gradient, because otherwise it means that your press is not efficient (no extraction of water). The only thing you try to obtain is a symmetric profile and this is exactly what Joel said before. So how did you run the press sections in your machine?

Doug Coffin Miami University, Oxford, OH

I am just trying to think about how to interpret all this. You have bending stiffness measurement, you have elastic stiffness measurement, you have caliper measurement, the same density, we can assume constant caliper which means your results for roll nip and shoe press are different. But did you calculate bending stiffness based on the modulus times thickness squared to see if your measurements are above or below the calculated value. Then you get the idea of whether you have a different structure or not and so you can look at the roll and shoe and decide which one is losing and/or which one is gaining?

Paul Krochak

No that would be actually interesting to do. I never thought about that.

Torbjörn Wahlström Stora Enso

I just realized that I have grown old enough to make a retrospective reflection. When I was working for Valmet in the 1990s and we developed this shoe pressing it was sold as creating a gradient effect which was obviously wrong. The misunderstanding was that the density versus dryness relation which explains why you get better bending stiffness for a certain dryness was mistaken for a gradient effect. Maybe it is worth mentioning calendaring where you really create a densification of the surface but that is of course due to the addition of heat and sometimes also moisture that makes the surface softer and then you get a real gradient effect.

Paul Krochak

And that is a good point I mean you need to have moisture or water to create a density gradient.

Joel Panek WestRock

There are still some open ends on this. What do you think would be good things to measure and analyze to clarify. Presumably you still have samples remaining. For you and for the audience, what else could be analyzed on the samples to better clarify what is driving this? Any suggestions?

Paul Krochak

I have thought about this, but it's not really fresh in my mind.

Joel Panek

Yes, it's not obvious. Does the method you've used for density distribution have a resolution for detecting fines. Is there a fines gradient through this, or a lack of fines gradient?

Paul Krochak

That is actually a really good question and I don't have an answer for this so please don't ask me, but I think that's actually an excellent question. Okay, because what we did was we said okay we will get approximate 10% increase in tensile strength and we just pretended that is proportional to density which I know given we just saw the Page equation that the reality is a little more complex. However, we can account for tensile increase by our estimated density increase, so one question we have, and have had, is what is the fines distribution? If we assume that there is some sort of ceiling effect, maybe all the fines are getting trapped in here. We don't know. We did actually try to measure this but we did it, let's say the poor man's way, so we took some samples, we slashed them, ran through the screen and then a fibre tester and we did not see the difference. But this does not mean anything because the fines often tend to be attached to the fibres and they don't want to come off. So there are better ways to do that, I think that is actually an excellent question. Another question, now I don't know exactly how accurate it is, but if you were to do shear profile measurements in the thickness direction, I don't know what kind of resolution you can get out here, but I think that will be very interesting because that will certainly go in and probe the thickness direction. But the fines, that is an excellent question, and that is one to say what did we see when we did these measurements? Again, from the fibre analyzer we saw that the fibres in the low press samples were a little bit more kinked, a little bit more deformed, but we saw zero difference in fines contents but again that does not mean anything. Maybe there is no difference, maybe there is, but I think that is hugely interesting to know, you know, and it gives you another tool to try and control the fines distribution in the thickness direction.