Reinforcing folding boxboard ply stock with refined pulp and its effect on dewatering potential

ANTTI I. KOPONEN, JUAN CECCHINI, MERJA SELENIUS, AND ARI JÄSBERG

ABSTRACT: The folding boxboard (FBB) filler ply typically contains a significant amount of mechanical pulp such as bleached thermomechanical pulp (BTMP), bleached chemi-thermomechanical pulp (BCTMP), and chemi-thermomechanical pulp (CTMP), etc. It is usually reinforced with either refined broke from the same paper machine line and converting process or by utilizing traditional bleached kraft pulp (BKP).

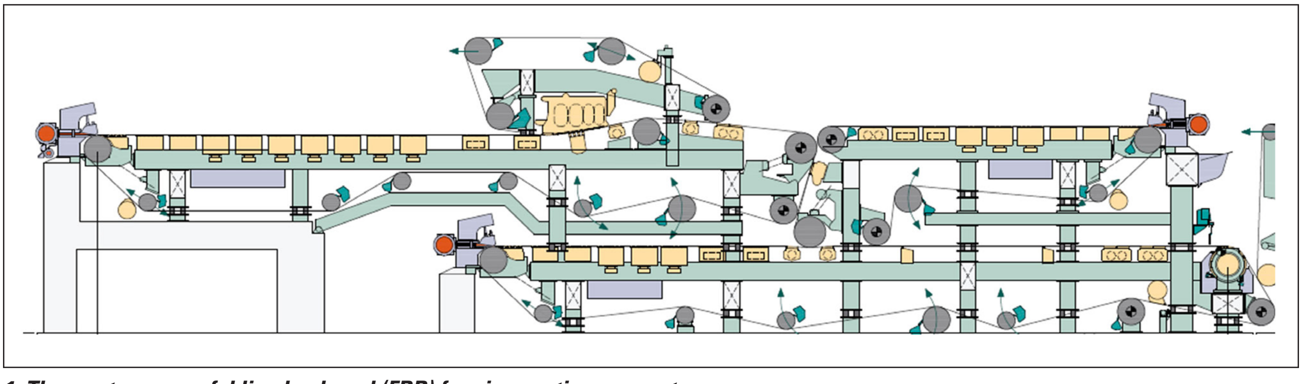
In response to the drive for improved/increased ply bond (to avoid undesired delamination), increased bulk, reduced basis weight, and minimized energy consumption, papermakers have experimented with various options and strategies. In between the common approaches, choices have been made between reducing the refining of the mechanical pulp, increasing the broke refining (more frequently practiced on the production scale), or increasing the BKP refining (a potentially superior choice).

This study focused on a simplified approach to assess the impact of three reinforcement pulps with different refining levels on the dewatering of the filler ply. The reinforcement pulp was added to the core stock for the FBB filler ply — a mechanical pulp, BCTMP, with a drainability of 25 °SR. The proportions of the reinforcement pulp, hardwood bleached kraft pulp (HWBKP), were 20% of 30–35 °SR, 10% of HWBKP 50–55 °SR, and 5% of HWBKP 70–75 °SR. The intention behind using varying percentages of reinforcement pulp was to attain a controlled internal bond while enhancing bulk through increased mechanical pulp content. The dewatering potential of the stock mixtures was assessed at three vacuum levels — 4, 10, and 25 kPa — that can be found in progressive stages within production-scale forming sections. Our goal was to find an optimal reinforcement strategy for filler ply that would minimize the use of the reinforcement pulp, give better strength, retain bulk, and lower basis weight. The success of this strategy was verified with an actual FBB machine.

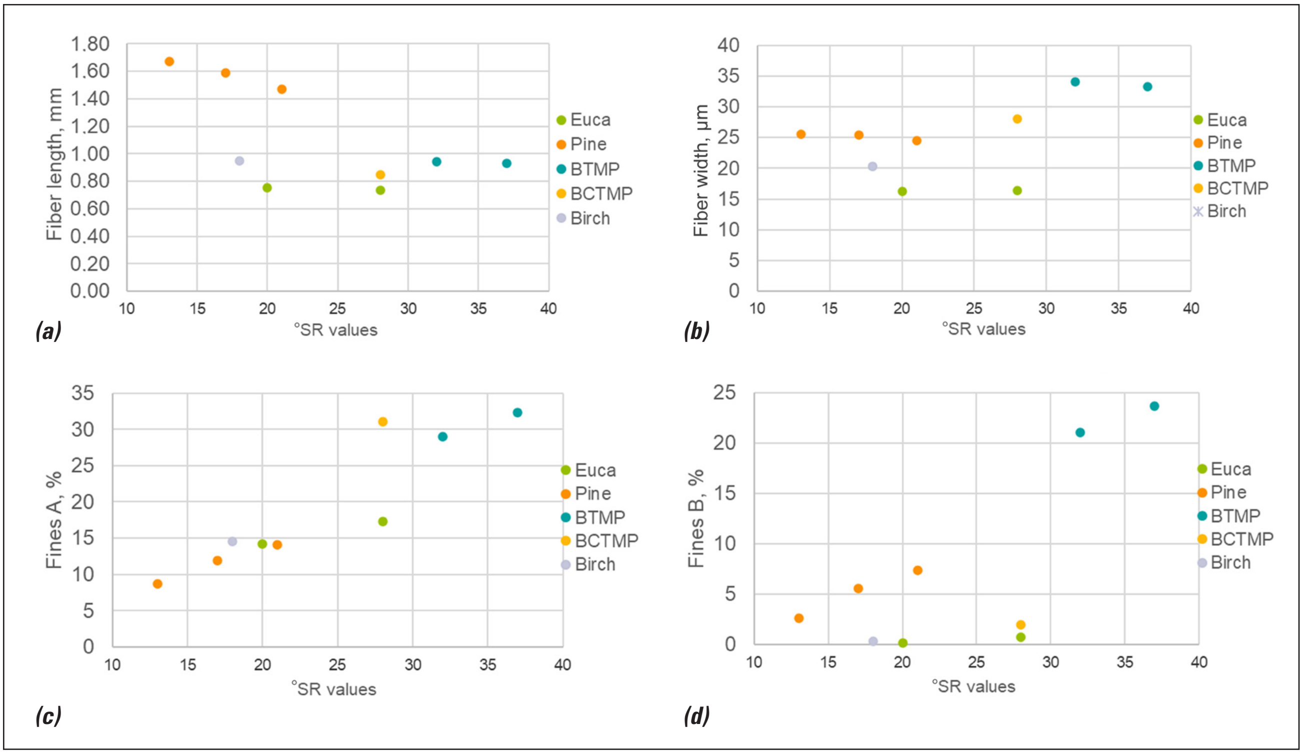
Application: This study introduces an improved reinforcement stock strategy that potentially improves dewatering and allows paper and boxboard makers to enhance product quality while achieving basis weight reductions.

The production of folding boxboard (FBB) consists of making a 3-ply structure in most cases. The outer (top and back) plies usually contain a mixture of chemical pulps like hardwood bleached kraft pulp (HWBKP) and softwood bleached kraft pulp (SWBKP). The filler ply (middle ply) contains mainly mechanical pulp that provides bulk and stiffness [1], as well as some chemical pulp, both of which have been refined to some extent. In addition, one can add some broke that is available from the production line and its converting process. Broke is a combination of mechanical and chemical pulp that also contains a certain amount of filler and pigments coming mainly from the coating process. [2]

The most common FBB forming section concept is shown in **Fig. 1**. In this concept, outer plies (surfaces) are based on Fourdrinier formers, while filler ply is typically handled with a hybrid former. The filler ply provides the bulk and core stiffness to the final product while the outer surfaces provide the smoothness and finishing properties. Most of the high-performance FBB products include coat-



1. The most common folding boxboard (FBB) forming section concept.



2. Example of characteristics of various FBB stock components as a function of drainability (°SR level): eucalyptus bleached kraft pulp (BKP), pine BKP, bleached thermomechanical pulp (BTMP), bleached chemi-thermomechanical pulp (BCTMP), and birch BKP. (a) Fiber length, (b) fiber width, (c) Fines A percentage, and (d) Fines B percentage.

ing to top (print) ply surface. The back (reverse) ply could optionally be coated if the back ply will be in indirect or direct contact with the product to be packed in the final box to be produced.

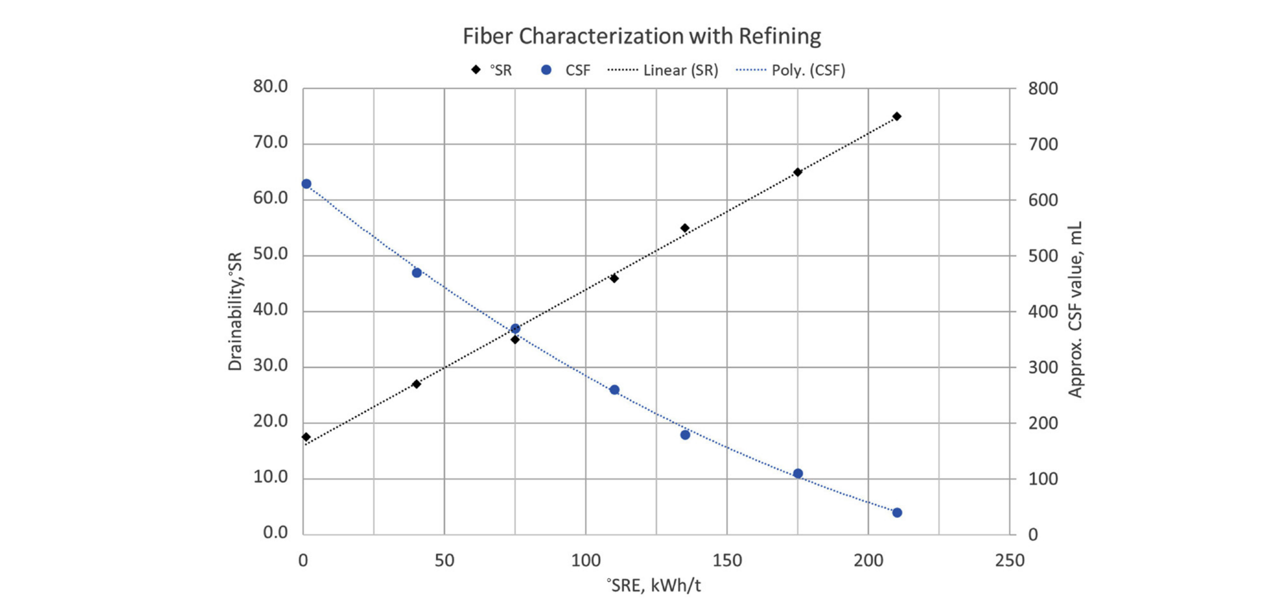
The challenge in the FBB final product is to maximize the bulk and stiffness while conferring good finishing for an appealing look in the final product for packaging purposes. Here, it has been a trend to maximize the mechanical pulp content and minimize the chemical pulp content while reducing the final product basis weight. One should note, however, that bulkier products with a high content of mechanical pulp tend to have challenges in achieving acceptable internal bond that enables suitable delamination in filler ply while executing the box folding. Moreover, reaching sufficient relative bonded area to prevent delamination during printing processes may also become problematic.

There has been a trend towards reducing the refining of mechanical pulp that is compensated for with additional refining of the reinforcement stock related to the filler ply. A common choice has been the use of refined broke for reinforcement purposes. However, since broke has a significant portion of mechanical pulp, it might not be an optimal choice for reinforcing. This is due to it having a considerable amount of mechanical fines, which are not likely to improve bonding but will be detrimental to dewatering performance. For this reason, the use of BKP as the reinforcement pulp with higher refining levels should be studied.

In the forming section of a paper machine, water is removed from the stock during the initial dewatering process using an increasing vacuum. Vacuum boxes, positioned underneath the wire, are used to apply controlled suction to extract water from the stock without damaging the sheet. By optimizing the forming section dewatering, it is possible both to improve the quality of the final product and to save energy. The so-called sheet sealing effect (densification of the fiber sheet close to the wire) is then also eliminated. The optimal pressure profile, in terms of shape and strength, depends on the composition of the stock and its dewatering properties.

The ability to characterize the dewatering properties of pulp is crucial in papermaking. This is usually done using either the Canadian standard freeness (CSF) or the Schopper-Riegler (SR) freeness test, which is expressed in °SR. While freeness has proven useful for industrial applications, it has some limitations. It serves as an empirical measure of pulp drainability, but its physical interpretation is not straightforward. Additionally, since the freeness test relies solely on gravity, it does not accurately reflect the true dewatering potential of the stock, limiting its effectiveness in capturing real-world dewatering conditions. In this work, a vacuum-assisted sheet former is used to assess the dewatering potential more realistically.

In this study, based on a real-world case, we investigated the use of chemical pulp as a reinforcement pulp for the filler ply in conventional FBB that is used for products such as cereal boxes. The overall goal of this project was to find



3. Hardwood bleached kraft pulp (HWBKP) drainability response (°SR and CSF) to specific refining energy input (SRE: specific refining energy).

an improved reinforcement strategy for the filler ply that minimizes the use of reinforcement pulp, gives better strength properties (especially higher internal bond), retains bulk, and lowers basis weight.

The experimental work presented in this paper focused on the filler ply composition alone and was based on the hypothesis that delamination within that ply will be a key point of vulnerability. In the experiments, the reinforcement pulp was added to the core stock for the filler ply, which consisted of a mechanical pulp, bleached chemi-thermomechanical pulp (BCTMP), with a drainability of 25 °SR. The proportions of the reinforcement pulp, HWBKP, were 20% at 30–35 °SR, 10% at 50–55 °SR, and 5% at 70–75 °SR. The intention behind using varying percentages of reinforcement pulp was to attain a controlled internal bond while enhancing bulk through increased mechanical pulp content. To ensure that the new reinforcement strategy would not negatively impact water removal, and potentially even enhance it, the dewatering potential of the three stock mixtures was tested with a vacuum-assisted sheet former at three vacuum levels — 4, 10, and 25 kPa — that can be found in progressive stages within production-scale forming sections. The obtained results encouraged further testing of this novel reinforcement strategy on an actual FBB machine.

MATERIALS AND METHODS

Furnishes

Outer FBB layers are typically made of a combination of HWBKP and SWBKP, while the filler ply is typically made of mechanical pulp mixed with broke and some amount of BKP. The mechanical pulp could be bleached thermomechanical pulp (BTMP), chemi-thermomechanical pulp (CTMP), or BCTMP. The selection of one or another might depend on the existing pulping line at the mill site, resulting in BCTMP as one of the most common cases. **Figure 2** shows the fiber lengths, fiber widths, and percentages of the A-type and B-type fines (flakes and fibrils type elements) for the various pulps measured with the FS5 Fiber Analyzer (Valmet Automation; Kajaani, Finland).

In most production scale cases, mill broke is incorporated in the filler ply. As the mill broke contains 65%–70% mechanical pulp, it typically has a drainability on the order of 30 °SR, while refined broke has typically a drainability on the order of 35 °SR. In those conditions, the broke is considered as reinforcement pulp. Since broke is a mixture of chemical and mechanical pulp, it does not necessarily give acceptable reinforcement performance. In such cases, the filler ply requires the addition of some extra amount of refined BKP.

This study hypothesizes that refined BKP is the best choice for reinforcement pulp. In particular, HWBKP is of interest due to two potential cost-saving benefits, namely, lower price and lower refining energy requirements when compared to SWBKP. Moreover, the hemicellulose content of hardwood is higher than for softwood, which might potentially improve the strength of the filler ply. While broke is cheaper, an optimized low amount of HWBKP with an optimized refining degree might provide extra benefits. The subsequent increase in mechanical pulp could enhance the bulk, stiffness, and internal bond of the board in particular.

To simplify the water removal study, we used as the core stock BCTMP 25 °SR in combination with three HWBKP (eucalyptus) pulps that were refined to °SR levels of 30–35, 50–55, and 70–75. **Figure 3** shows the refining curve development for HWBKP as a function of specific energy consumption (SEC). **Figure 4** shows the fiber length, fiber

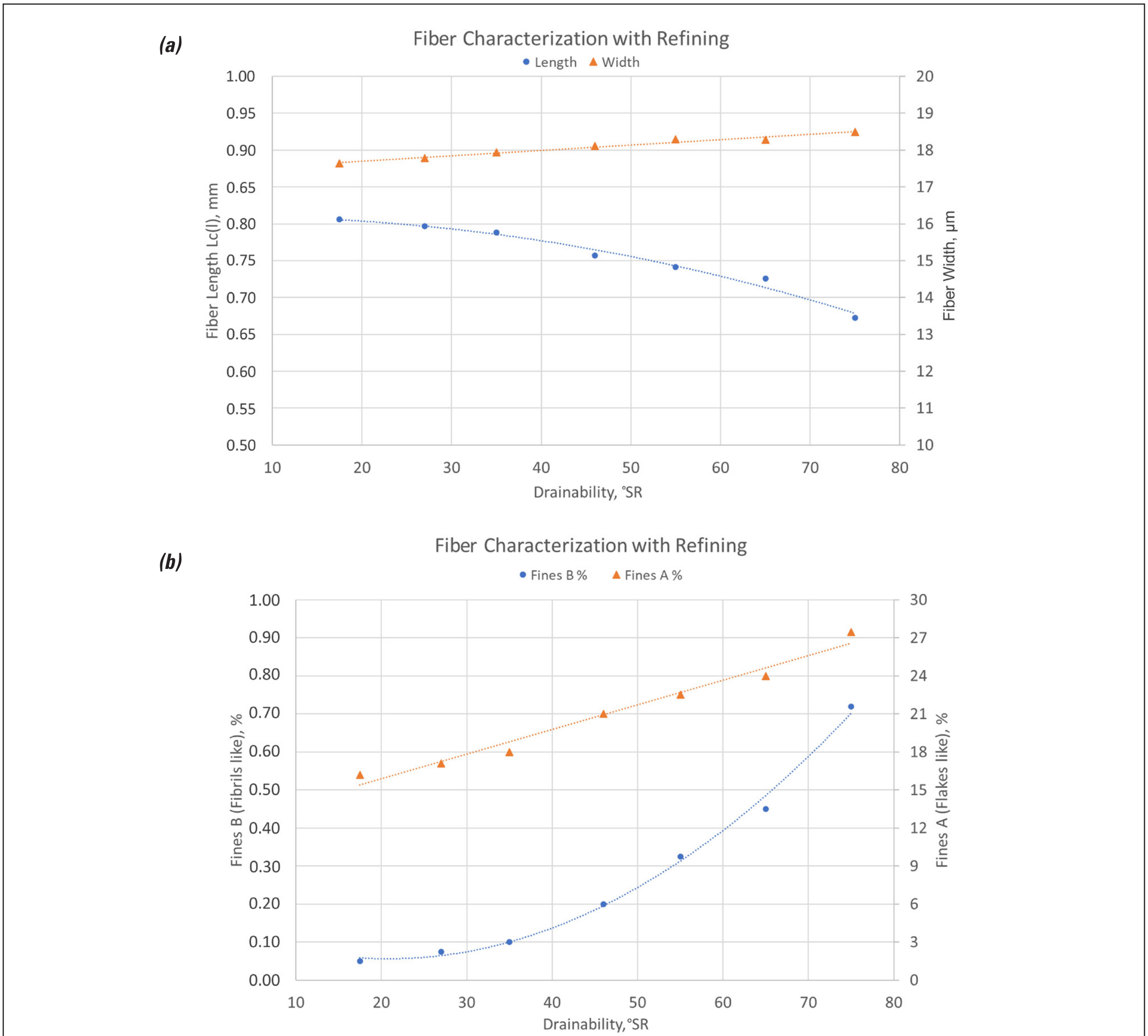
Stock	Pulp 1	Share, %	°SR	Pulp 2	Share, %	°SR
80/20	BCTMP	80	25	HWBKP	20	30-35
90/10	BCTMP	90	25	HWBKP	10	50-55
95/5	BCTMP	95	25	HWBKP	5	70-75

I. Composition of the studied stocks (BCTMP: bleached chemi-thermomechanical pulp; HWBKP: hardwood bleached kraft pulp).

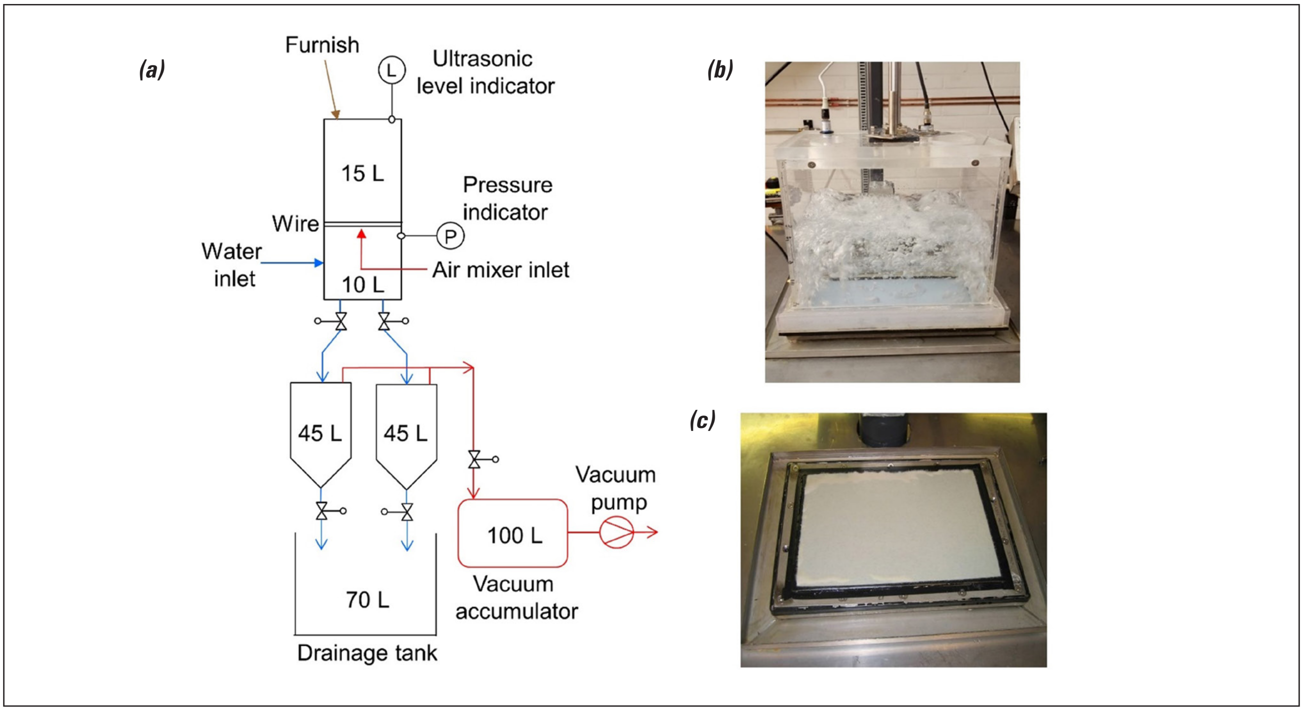
width, and percentages of the A-type and B-type fines as a function of drainability for HWBKP. **Table I** shows the composition of the studied stocks. The intention behind using varying percentages of reinforcement pulp having different refining levels was to attain a controlled internal bond while enhancing bulk through increased mechanical pulp content.

Vacuum-assisted sheet former

The forming studies were performed with a vacuum-assisted sheet former (**Fig. 5a**). Water removal can be performed with the device with adjustable vacuum levels from 4 to 70 kPa. Such a vacuum's operating range is comparable with those used in actual paper machine forming sections. The operational details of this device have been described in [3,4].



4. The HWBKP fiber characteristics as the function of drainability. a) length and width, and b) Fines A & B.



5. Forming laboratory device: (a) Schematic of the vacuum-assisted sheet former; b) pulp chamber during mixing of the stock by injected air; and c) wet sheet on the wire after forming [4].

At the beginning of processing, the water inlet valve was opened and kept open until the mould was filled up to the level of 50 mm. Then, the fiber suspension was added to the mould and the mould was filled with process water up to the 200 mm level. Finally, the suspension was mixed by injecting air from below the wire (Fig. 5b).

During drainage, a wet sheet was formed on the wire (Fig. 5c). After forming, the sample was collected for determination of retention. In addition to the time evolution of vacuum, $P(t)$, measured below the wire (**Fig. 6a**), the time evolution of the position of the fiber suspension surface, $h(t)$, was measured with an ultra-sonic detector (Fig. 6b).

In this study, the forming consistency was ca. 0.12%. Vacuum levels during the experiment were 4, 10, and 25 kPa, and basis weight was 240 g/m². The stock temperature was 20°C during forming. At this temperature, the viscosity of water is 1.0 mPas.

Resistivity of the filtered sheet during forming

The flow of water through a filtered sheet can be described by Darcy's law [5]:

$$v = \frac{k}{\mu}\frac{P}{L} \tag{1}$$

where v is the superficial velocity of water; μ is the water dynamic viscosity; P is the pressure difference over the sheet; L is the thickness of the sheet; and k is the sheet permeability. In practice, the determination of the thickness of the fiber sheet is challenging during the filtering process. In such a case, Darcy's law (Eq. 1) can be written in the form:

$$v = \frac{P}{D\mu} \tag{2}$$

where D is the drainage resistance of the sheet. If the basis weight is known, Eq. 2 can be written in the form [6]:

$$v = \frac{P}{K\mu \cdot \mathrm{BW}} \tag{3}$$

where BW is the basis weight, and the resistivity of the filtered sheet, K, is defined as:

$$K = \frac{D}{\mathrm{BW}} \tag{4}$$

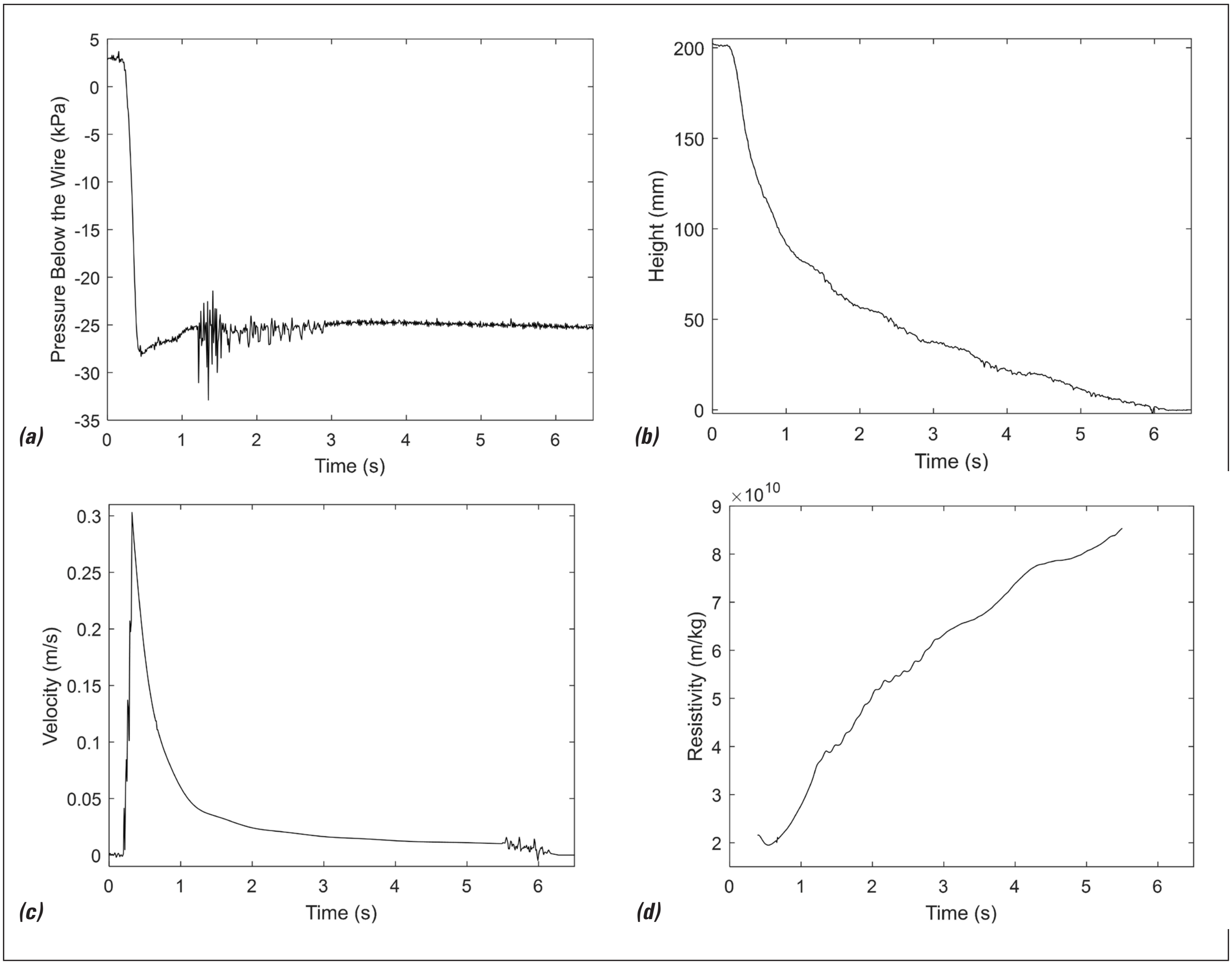
In the vacuum-assisted sheet former, one must consider both the flow resistance, R, due to the wire, and the hydrostatic pressure of water, $\rho g h$. In this case, the velocity during the forming process is at time t:

$$v(t) = \frac{P(t)+\rho g h(t)}{K(t)\mu \cdot \mathrm{BW}(t)+R\mu}. \tag{5}$$

Following references [7-9], we use the formula below:

$$K = \beta P + \alpha I + \gamma \tag{6}$$

for modeling resistivity. Above, $I = \int_0^t P dt'$ is the pressure impulse density, and β, α, and γ are pulp-dependent material parameters. The model assumes that the sheet behaves



6. Examples of measurements from the forming laboratory device: (a) pressure under the wire during forming; (b) height of the fiber suspension column during forming; (c) velocity of the suspension surface calculated from the height data.; and (d) resistivity of the filtered sheet calculated from Eq. 5 [4] .

as a first-order approximation like a viscoelastic Maxwell material, wherein the elastic behavior of the sheet is reflected in the term βP, and the plastic behavior is reflected in the term αI. The parameter γ is called the zero-pressure resistivity of the stock. We want to emphasize that the resistivity K is not constant but depends on the vacuum level and the duration for which the vacuum is applied.

RESULTS AND DISCUSSION

Water removal time

Figure 7 shows the measured suspension column height as a function of time for the different mixtures with different vacuum levels. We see that the difference in the water removal times is relatively small. However, with all vacuum levels, the water removal time of the 95/5 mixture is slightly lower than with the other two stocks.

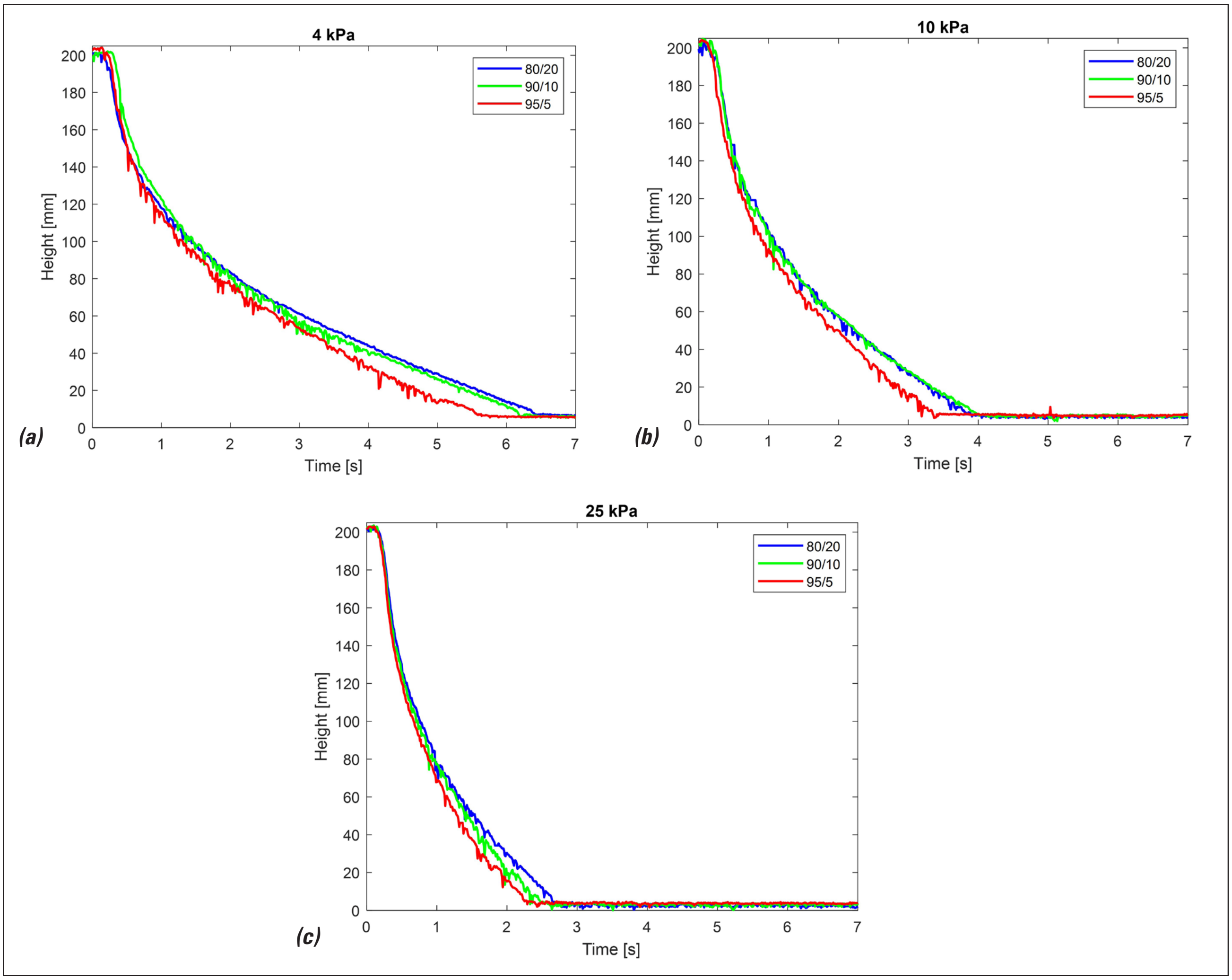
A regression analysis was performed, where the dependent variable was the water removal time, T (s), and the vacuum level, P (kPa), was the independent variable. The following power law-type model worked very well (R^2 = 0.99):

$$T \propto P^{-0.5}. \tag{7}$$

The water removal time is not inversely dependent on the vacuum level, as the resistivity of the sheet increases with increasing vacuum level due to compression of the sheet. Notice that in [4], the exponent got similar values in the °SR range of 43–85. By iteratively solving Eqs. 5 and 6 using the model parameters in Table II, we obtained the following correlation (R^2 = 0.99) between water removal time and basis weight for the three mixtures within a basis weight range of 120–240 g/m² and a vacuum range of 14–28 kPa:

$$T \propto \mathrm{BW}^{1.1}. \tag{8}$$

In [4], the exponent was similar for a 43 °SR furnish.



7. The measured suspension column height as a function of time for the different stock mixtures with different vacuum levels of: a) 4 kPa, b) 10 kPa, and c) 25 kPa.

Resistivity of the stocks

We used Eq. 5 to calculate the time evolution of the resistivity K of different stocks (Fig. 6d). Here, the velocity $v(t)$ was obtained from the measured $h(t)$-curve by numerical differentiation (Fig. 6b and Fig. 6c). The basis weight of the filtered sheet during forming was estimated from the equation

$$\mathrm{BW}(t) = \frac{h(0)-h(t)}{h(0)} \cdot \mathrm{BW}_{\mathrm{sheet}} \tag{9}$$

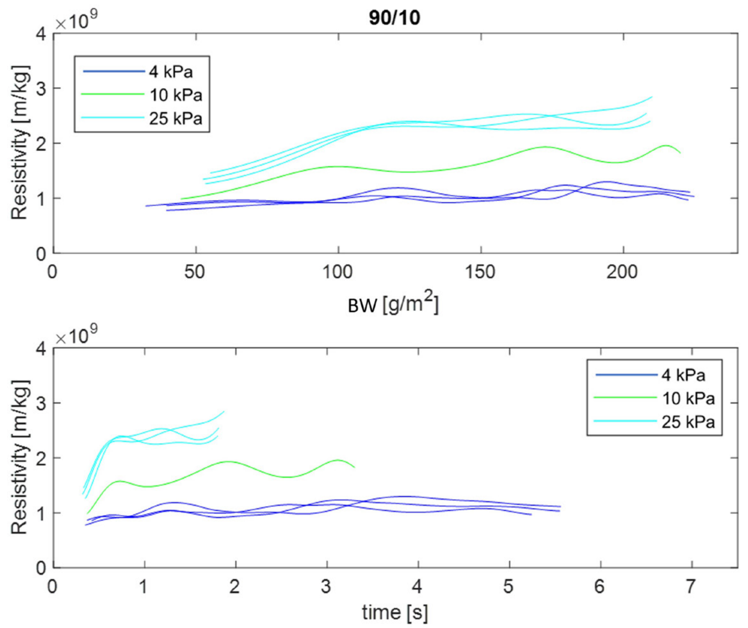
where $\mathrm{BW}_{\mathrm{sheet}}$ is the basis weight of the final wet paper sheet. It is assumed that retention is constant during the filtering process. This assumption has earlier worked well for various furnishes with °SR values below 85 [4,9].

When calculating the resistivity, the measured vacuum, $P(t)$, and height, $h(t)$, were replaced with a high-order polynomial fit to the measured values to decrease the noise level in the experimental data. The fit was made for the measurement points with 5 mm < h < 190 mm. Points outside this region were omitted in the resistivity analysis. The success of this approach is reflected in the rather smooth dependence of the calculated resistivity on time and basis weight (**Fig. 8**). The combined flow resistance of the wire and the porous plate supporting it was estimated to be $R = 3 \times 10^6$ 1/m. Its effect on the total flow resistance was thus negligible.

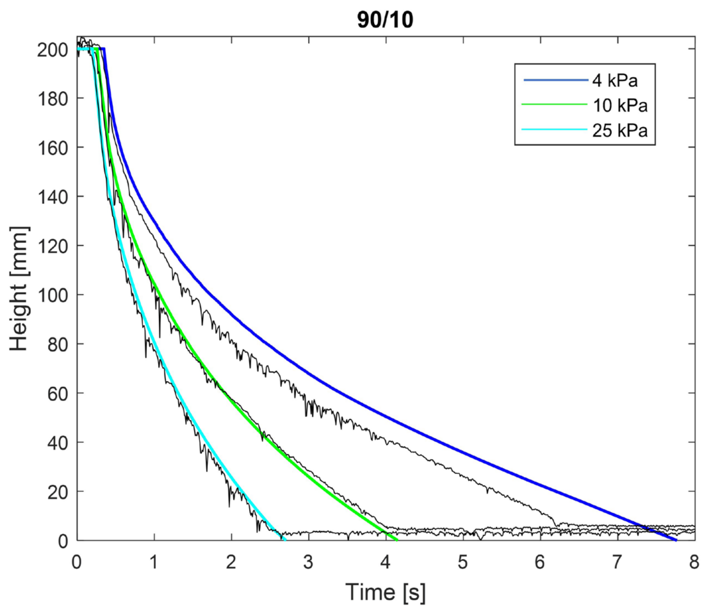
Figure 8 shows the resistivity as a function of the basis weight and time of the filtered sheet for the 90/10 stock. For the other two stock compositions, the curves were qualitatively similar. We see that resistivity increases with increasing vacuum levels due to the compression of the sheet [10].

Model for resistivity

Equation 6 was used as the model of the sheet resistivity. **Table II** shows the fitted coefficients β, α, and γ of the model for the different pulp mixes. Generally, the coefficients decreased with increasing amounts of BCTMP. The value of coefficient β, which shows the dependence of resistivity on the vacuum level, is 20% smaller for the 95/5 stock when compared to the 80/20 stock. The higher con-



8. Resistivity as a function of basis weight and resistivity as a function of time for the 90/10 mixture. The waviness of the curves is due to slight fluctuations in the vacuum level during operation.

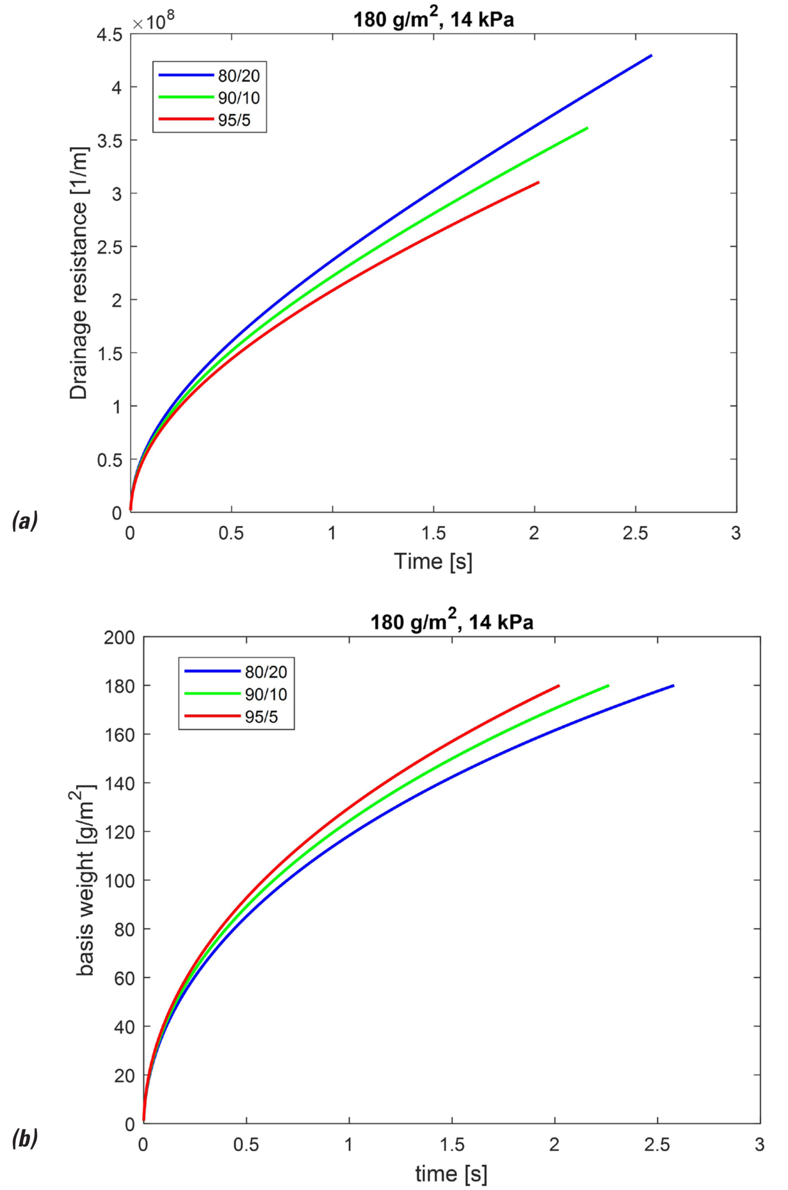


9. The measured and modeled suspension column height as a function of time for the 90/10 stock with different vacuum levels.

tent of mechanical pulp thus clearly improves the dewatering performance of the stock. On the other hand, the value of coefficient α, which shows the tendency of the stock to compress inelastically due to vacuum, is 50% smaller for the 95/5 stock when compared to the 80/20 stock. While this is related to improved dewatering potential, it could also be interpreted as an improved ability of the stock to retain bulk during processing.

Figure 9 shows the measured and modeled suspension column height as a function of time for the 90/10 stock with different vacuum levels. The model curves have been iteratively obtained from the measured vacuum profile by using Eq. 5 and Eq. 6 and the model parameters of **Table II**. We see in Fig. 9 that the model works quite well, with the difference of the measured and modeled curves being slightly higher with the lowest vacuum level.

Figure 10 shows for the 20 cm suspension column height the modeled drainage resistance (see Eq. 2) and the

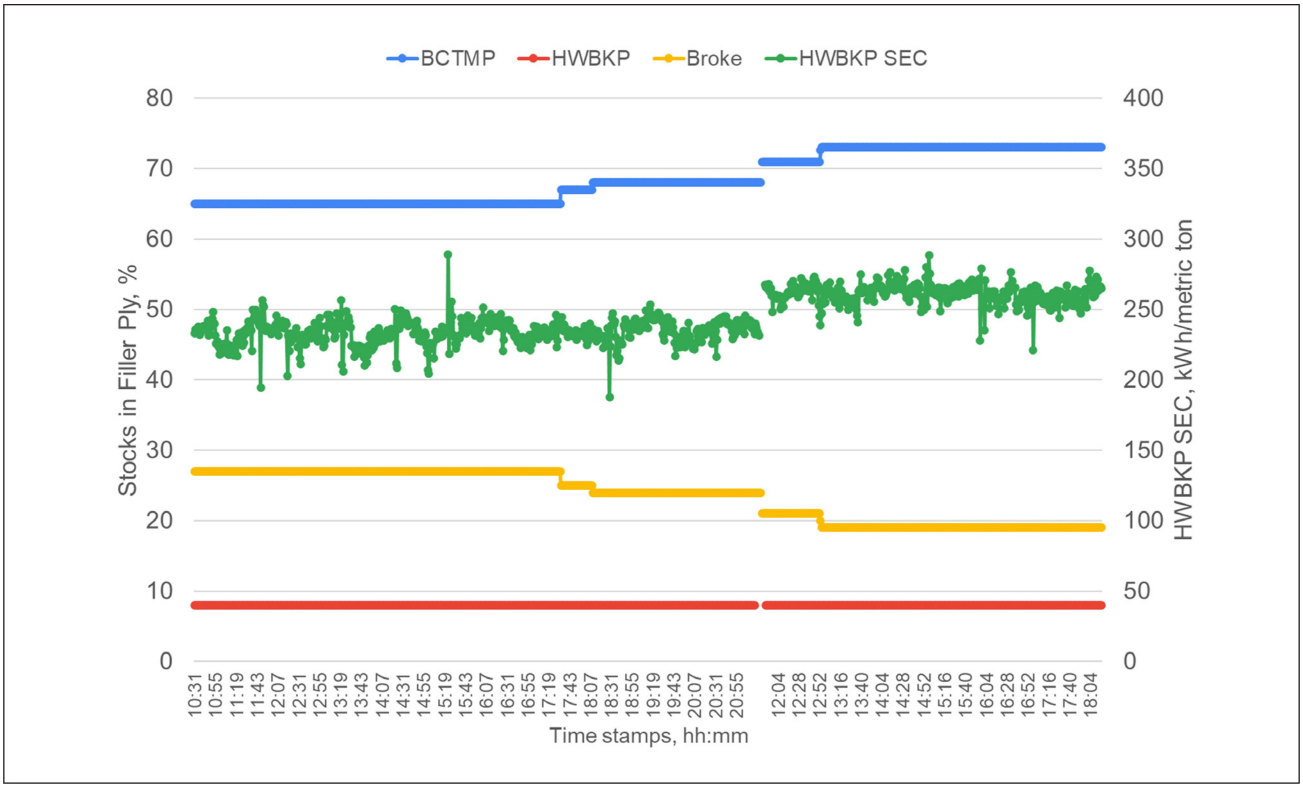


10. (a) Drainage resistance as a function of time; and (b) basis weight as a function of time for the three different stock mixtures. The vacuum level is 14 kPa and the basis weight is 180 g/m².

basis weight as a function of time for the different stock mixtures for the basis weight of 180 g/m² and a vacuum level of 14 kPa. The samples containing a higher amount of BCTMP but a higher degree of refining in reinforcement pulp are seen to perform better in dewatering. The water removal time is 25% smaller for the 95/5 stock when compared to the 80/20 stock. With a lower suspension column height (such as the typical slice opening, which is in the

Stock	β x 10^{-6}, m^2s^2/kg^2	α x 10^{-6}, m^2s^2/kg^2	γ x 10^{-6}, m/kg	R^2
80/20	0.0631 ± 0.0008	0.0189 ± 0.0007	796 ± 9	0.99
90/10	0.0514 ± 0.0008	0.0141 ± 0.0008	826 ± 9	0.98
90/5	0.0513 ± 0.0007	0.0100 ± 0.0008	714 ± 8	0.97

II. The coefficients of the model Eq. (6) for the different stocks.



11. Stock composition (BCTMP, HWBKP, and broke) in the filler ply and refining level of HWBKP as a function of time during the change of the stock composition. The experiment was performed during successive days (SEC: specific energy consumption).

order of 1 cm), the benefit will be smaller, but it remains significant from a practical standpoint.

The reason behind the improved dewatering might be the fact that a web structure having a higher content of mechanical pulp might densify less than others with higher chemical pulp content. This could be explained by a higher porosity of the web structure despite the higher content of fines; this could leave more open channels in the web structure for dewatering. Generally, it is preferable to minimize the amount of the reinforcement pulp by increasing refining to maximize the amount of the mechanical pulp in the filler ply. These results suggest that this approach does not compromise the water removal potential of the stock; in fact, it may enhance the water removal efficiency.

Stock composition study on an FBB machine

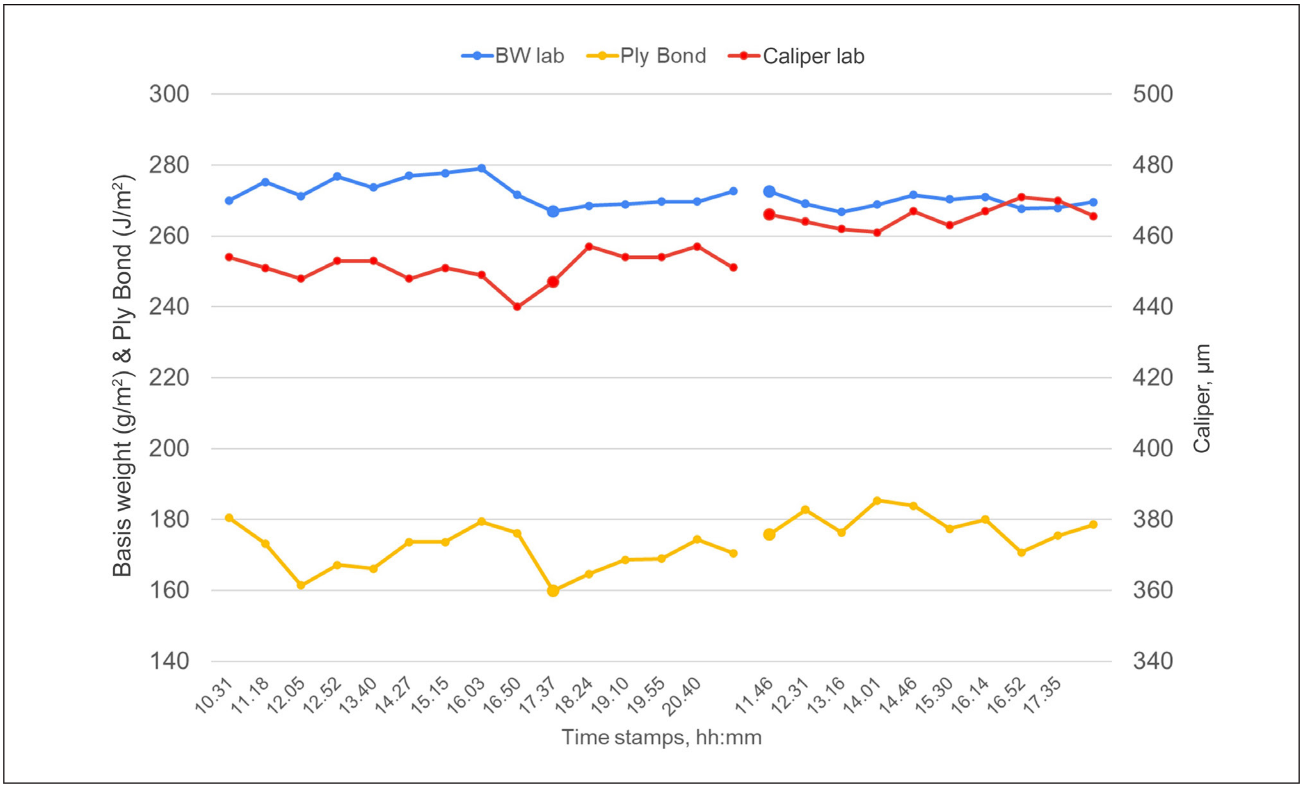
The improved reinforcement strategy for filler ply was tested on an FBB machine. During this test, the amount of broke was simultaneously decreased, increasing the BCTMP content. The HWBKP content was kept fixed at 8%, and its refining level was raised during the test run. **Figure 11** shows the stock composition (relative fractions of BCTMP, HWBKP, and broke) as a function of time during the stock composition change, together with the specific HWBKP refining energy. **Figure 12** shows the basis weight, thickness, and ply bond of the board, whereas **Fig. 13** shows the bulk and the Taber geometrical bending stiffness. When comparing the board properties before and after the composition change, we see that the basis weight of the board has slightly decreased while the bulk has clearly increased. Moreover, the internal bond and the bending stiffness of the board have simultaneously increased.

The machine speed was 800 m/min and the width was 6 m. This indicates production savings of the order of 50 metric tons/day. If we assume the price of the product to be 1500 €/metric tons, the benefit in income is of the order of 75000 €/day and 30 M€/year. The change in the stock composition could therefore yield significant benefits for the company.

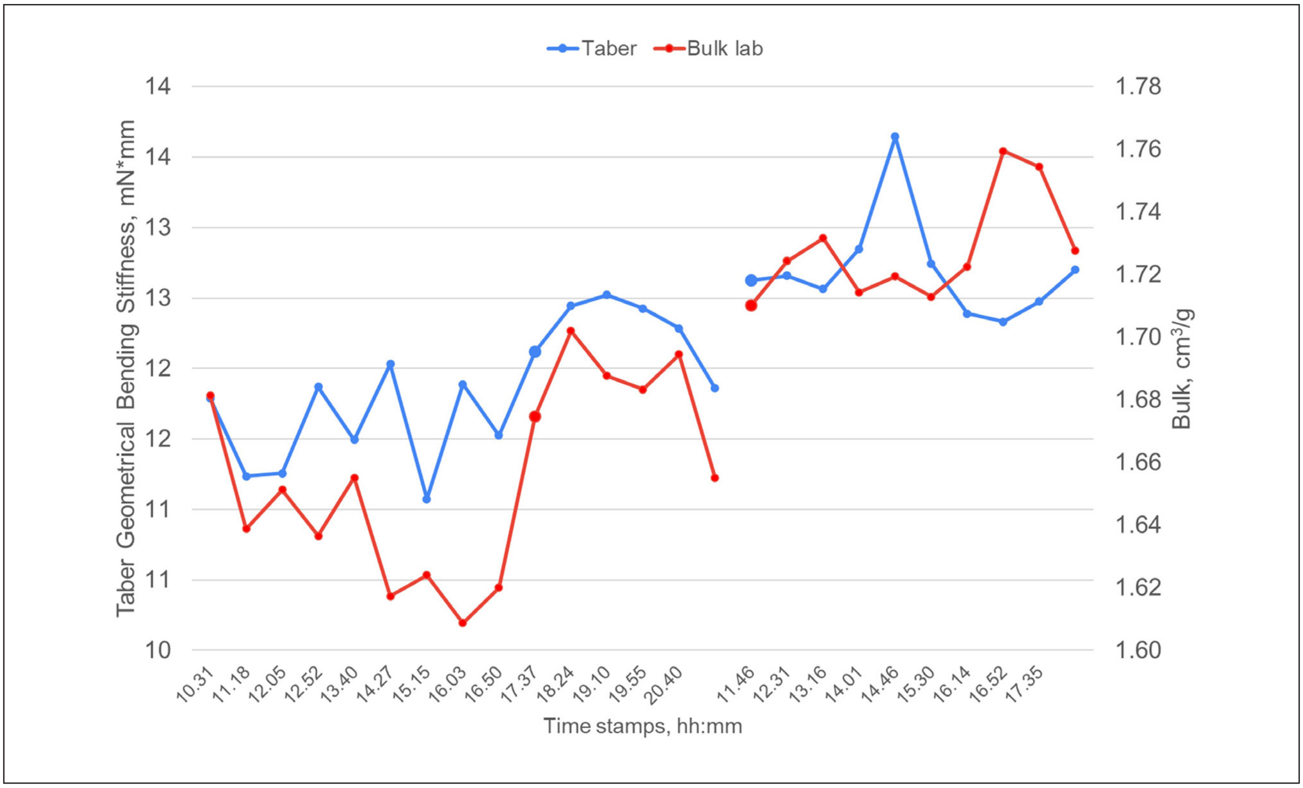
CONCLUSIONS

To improve the cost efficiency of FBB products, increasing mechanical pulp content is the target of many paper and board makers while reducing basis weight and simultaneously achieving good bulk, stiffness, and internal bond development in the final product. This can be archived by decreasing the amount of hardwood pulp used as the reinforcement pulp by simultaneously increasing its refining level to maintain the interfiber bonding. Each type of pulp has a different role in the web structure's characteristics and properties.

Increasing HWBKP refining while reducing its applica-



12. Laboratory values of basis weight (BW), caliper (thickness), and ply bond during the change of the stock composition. The experiment was performed during successive days.



13. Laboratory values of bulk and Taber geometrical bending stiffness during the change of the stock composition. The experiment was performed during successive days.

tion in the filler ply mix seems to improve the dewatering performance. Stiffer fibers, such as those from mechanical pulp, provide a more open pore structure in the fiber mat. Increasing its content helps to reduce web sealing compared to a web structure with a higher content of chemical pulp (flexible and bendable fibers).

This improved reinforcement pulp strategy has already been successfully implemented in production machine cases, allowing the paper and board makers to enhance product quality while achieving basis weight reductions. It is noteworthy that such improvements could be introduced by evaluating the actual process capabilities to appropriately treat each component of the stock.

For future work, it would be beneficial to investigate the effects of retention aid chemicals on dewatering. These chemicals can help bind cellulosic fines to fiber surfaces, reducing the likelihood of departing water pulling these particles into choke points within the wet web and thereby eliminating the sealing effect that impedes drainage. Here, careful optimization of the chemistry is needed, as a flocculated sheet may have poor strength properties. Addressing these factors is important for improving both the efficiency of water removal and the overall quality of the final product.

Another important question for future work is the use of dry-end broke for reinforcement. However, it can be challenging to identify clear differences that could be attributed to a single drying operation when working with otherwise identical fibers. Furthermore, if these broke fibers are subjected to refining, there is a risk of losing their essential bulkiness. Addressing these concerns in future studies could be valuable and help improve our understanding of the material's properties. **TJ**

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ABOUT THE AUTHORS

Papermakers face pressure to use more economical fibers while simultaneously achieving bulkier, stiffer, and stronger board structures. Reaching this goal is challenging and requires extensive analysis to evaluate various approaches. One crucial consideration in this process is ensuring that new stock recipes do not compromise water removal efficiency.

In this research, the approach to reinforce the folding boxboard (FBB) filler ply is innovative, and there is limited research on the effects of such stock composition changes on dewatering. Dewatering properties of stocks are typically evaluated using freeness measurements. In this work, a vacuum-assisted sheet former was employed to more realistically assess the dewatering potential.

One challenge in this study was that due to time constraints, it was not possible to conduct a systematic study in which the refining level and content of the reinforcement pulp were varied independently. Instead, we selected three compositions that appeared most promising from a practical standpoint.

We discovered that microfibrillated cellulose (MFC) is not required to achieve substantial strength improvement; this can also be obtained with highly refined furnish (HRF) using a relatively small addition of stock, while simultaneously achieving suitable dewatering for the FBB filler ply.

Koponen

Cecchini

Selenius

Jäsberg

It was interesting to see how optimizing paper properties goes hand-in-hand with optimized furnish handling, enabling the minimization of dosages and energy required for producing stock while enhancing dewatering. This is a challenging combination when aiming to improve paper quality.

The improved reinforcement pulp strategy presented here allows paper and board makers to enhance product quality while achieving basis weight reductions. Grades produced through multi-ply forming could benefit from manufacturing with a multi-layering headbox, enabling reduced basis weight while effectively controlling dewatering.

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