

# *Pilot-made, highly extensible paper for dry 3D forming*

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**ABSTRACT:** Cellulose fiber-based packaging materials must perform well in demanding three dimensional (3D) forming process conditions. On the other hand, the development of manufacturing concepts is required for improved competitiveness of bio-based materials. This study covers some key factors that influence the extensibility of cellulose fiber-based structures and presents a pilot-scale development study of a 3D formable material concept.

Bleached softwood kraft (BSK) pulp from a Nordic pulp mill was used in the pilot trials. Cellulose-based webs were formed using water-laid and foam-laid web forming using a pilot paper machine. For the water-laid forming, the BSK pulp was refined by applying a high consistency (HC) phase at over 40% consistency, followed by a low consistency (LC) refining at 4% consistency. The BSK pulp was refined for the foam-laid forming by only applying low-consistency refining. In the foam-laid web forming, anionic sodium dodecyl sulfate (SDS), two foamable latexes, and polyvinyl alcohol (PVA) were used as foaming agents. The pilot rolls were dried at a separate steam cylinder dryer pilot and compacted in-plane in the machine direction (MD) at a separate pilot machine. Tensile properties of the treated paper webs were measured and evaluated with respect to achieved web shrinkage. The same dimensional contraction brought by shrinkage was almost strained out in tensile testing.

The results indicated that the shrinkage that occurred by drying and in-plane compaction depended on the pulp furnish. The water-laid material achieved about 30% elongation, whereas the foam-laid material achieved significantly above 50% elongation. The 3D forming performance of the dry materials was tested using fixed and sliding blank methods. The dry paper sheets performed well enough in 3D forming for application to many consumer package applications according to their extensibility.

**Application:** Understanding the roles of web-forming methods, chemical additives, shrinkage, elongation, and strength is highly significant for developing new cellulose-based packaging products, particularly those intended for dry web 3D forming. A large improvement in dry web 3D forming performance of paper products can be reached only by applying in-plane compaction and optimal strengthening, as demonstrated in this investigation by the experimental pilot-scale tests.

In recent years, the development of bio-based packaging manufacturing technology concepts has been active and focused on improving bio-material competitiveness compared to oil-based plastic solutions. Reducing plastic waste and developing recyclable, reusable, and bio-disposable solutions made of bio-based renewable materials to replace oil-based plastic materials are important targets for many organizations. Large-scale industrial production requires efficient process concepts, such as the 3D forming of the dry paper web. In particular, when deeper shapes are created, the paper and board can replace plastics in certain packaging applications. The key material properties for industrial 3D-forming applications include the extensibility and the tensile strength of the paper [1,2]. The extensibility, i.e., the material's ability to elongate under external load, is low for both fibers and papers dried under restraint. Reviews [2-5] show that the extensibility of paper is governed by the behavior of single fibers, interfiber bonding [3], and network properties [2]. Recently, extensibility has been studied widely on several structural levels (fibers, fiber bonds, and network structure) for improved paperboard performance in packaging applications [2,6-16]. In

this study, extensibility describes the material's ability to elongate under complex circumstances, including non-planar forming forces and other conditions that differ from the standardized tensile testing of paper in which elongation is measured.

Commercial paperboard elongation has been reported as being between 2.5% and 8%, depending on the orientation direction [17,18]. Elongation above 20% in the machine direction (MD) can be achieved by creping tissue papers [19]. In-plane compaction (mechanical shrinking) operations can produce elongations above 10% in the MD for commercial paper grades. There are at least two technologies for in-plane compaction that are applied commercially: the trademarked Expanda and Clupak processes [20,21]. A high extensibility potential of paper can be obtained from the shrinkage of the paper [10]. The shrinkage, which is a negative strain and opposite to elongation, which is a positive strain, can be due to drying shrinkage or due to in-plane compaction forced by external forces. However, the elongation of an in-plane compacted fiber network can be utilized only when the interfiber bonding level is sufficient [12]. Interfiber bonding in paper is usually improved using,

|                                                                                                                                                                                   | HC (reference) | HC+LC        | LC           |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|--------------|--------------|
| Length weighted fiber length of pulp, mm                                                                                                                                          | 1.64 ± 0.02    | 1.73 ± 0.02  | 2.01 ± 0.01  |
| Length weighted fiber width of pulp, µm                                                                                                                                           | 27.65 ± 0.07   | 27.75 ± 0.07 | 29.60 ± 0.14 |
| Mean shape, %                                                                                                                                                                     | 76.8 ± 0.1     | 84.5 ± 0.3   | 84.6 ± 0.14  |
| SR number*                                                                                                                                                                        | 14             | 28           | 23           |
| HC: high consistency; LC: low consistency; SR: Schopper-Riegler (SR).<br>* As determined by ISO 5267-1 "Pulps — Determination of drainability — Part I: Schopper-Riegler method." |                |              |              |

I. Average fiber and pulp properties.

for example, refining of furnishes, strength additives, reinforcement fibers, and chemicals.

The opportunity to replace water with foam as a carrier medium in paper and paperboard making has been studied since the early 1970s [22-24]. Generation of an aqueous foam by adding some foaming agents to pulp suspension, followed by air injection under well-controlled conditions, can bring interesting opportunities for web forming [25,26]. As a result of the unique rheological properties of foam forming of fiber webs, using foam as a carrier was reported to give excellent uniformity [22-25]. In addition, significant improvement in bulk and softness of the end product was reported [26]. The main reported disadvantage of foam-forming technology was the deterioration of the strength properties of the web compared to the traditional wet-laid webs [22-24]. However, the strength loss can be compensated through more intensive wet pressing, leading to higher density or refining of the furnishes [22,23,25]. Recently, the advantages of using foam forming for development of bio-based structures for applications including paper, board, nonwovens, cushioning materials, wall panels, filters, and growing media for plants have been examined [15,16,27-30].

The objective of this work was to pilot and prove the complete production chain successfully, from pulp refining to 3D dry forming of shapes, using pilot scale machinery to obtain maximal extensibility. The best-known and available pilot methods were chosen and applied in the study. The details related to the pulp recipe and process operations after web forming were exploratory and not widely used for board making. Some of the recipes used in this investigation were tested earlier in a laboratory-scale study [16]. This investigation focused on the development of the extensibility of the material. For that reason, barrier layers were not applied, and barrier properties were not investigated.

EXPERIMENTAL

Materials

Raw materials

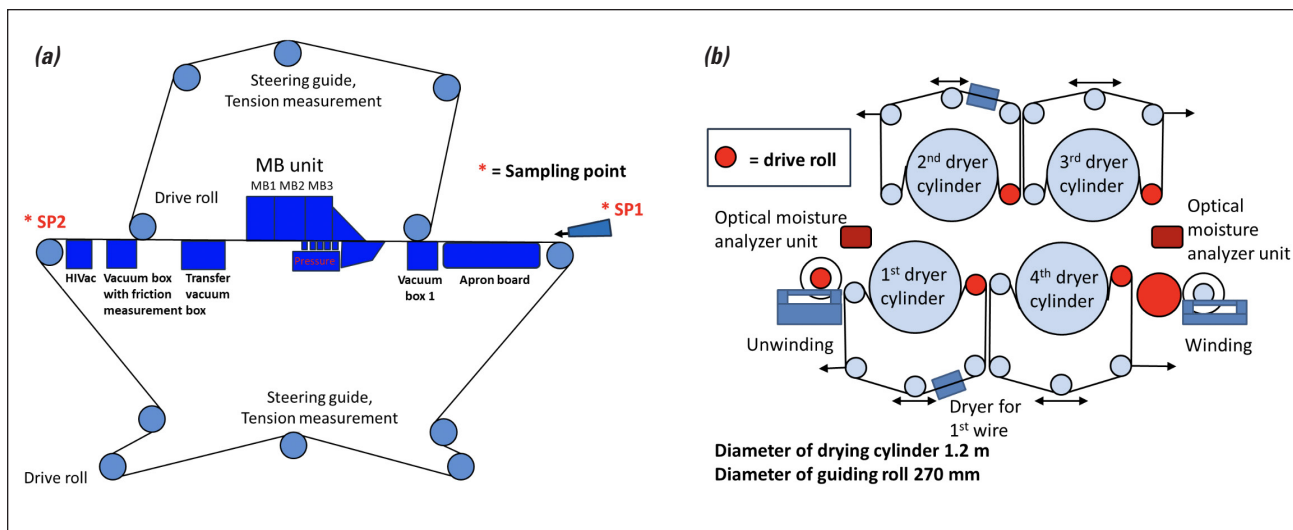
The raw material was a dried bleached softwood kraft (BSK) pulp from a Nordic pulp mill that was a mixture of spruce (*Picea abies*) and pine (*Pinus sylvestris*). Cellulose-based webs were formed using water-laid and foam-laid forming

using a pilot paper machine. For the water-laid forming, the BSK pulp was refined by applying a high consistency (HC) phase at over 40% consistency using a Sunds defibrator RGB 44, followed by a low consistency (LC) refining at 4% consistency using Valmet (Espoo, Finland) Optifiner RF1. Drainage of the pulp suspension as determined by the Schopper-Riegler (SR) method after HC refining and LC refining was 14.5 and 28, respectively. For the foam-laid forming, the BSK pulp was refined by applying LC refining at 3.5% using conical fillings in the refiner. The SR number after LC refining was 23. The applied specific refining energy (SRE) in the LC refining phase for the water-laid and foam-laid cases was 100 kWh/metric ton and 95 kWh/metric ton, respectively, and the specific edge load (SEL) was 2.4 J/m and 2.3 J/m, respectively. The measured specific energy consumption (SEC) in HC refining was 178 kWh/metric ton.

Fiber properties of the pulps (Table I) were measured with fibers in the swollen state using an L&W Fiber Tester Plus (ABB; Zurich, Switzerland). The HC+LC refined pulp was used in water-laid forming, and the LC refined pulp was used in foam-laid forming. As a reference, the HC refined pulp is also presented. The fiber length and width after LC refining were 2.01 mm and 29.6 µm, respectively, which were considerably higher compared to the reference samples. However, the pulp batches were different, and differences were more likely due to the different batches than the influence of refining. All the other fiber properties were quite similar between the pulps. The HC treatment of BSK pulp is known to increase both small- and large-scale fiber deformation, whereas LC treatment straightens the fibers without significantly removing small-scale deformations [3]. It can be estimated that the swelling ability and shrinkage potential of the LC-refined BSK pulp are good.

Other water-laid fibers

Polymeric bi-component (BiCo) fibers with polyethylene (PE) cover and polypropylene (PP) core were used. The fibers were WL Adhesion C from FiberVision with a length of 3 mm, and the linear density was 1.7 dtex. Decitex (dtex) is a metric unit for the linear density of fiber and is mainly used for continuous filament yarn, defined as the mass in grams per 10,000 m. Properties of the individual BiCo fibers were as follows: Density 1.155 g/cm³, tensile strength



**1. Schematic layouts of: a) forming section used in the pilot trials, and b) pilot cylinder dryer used to dry the samples (MB: multi-blade dewatering unit; SP: sampling point).**

(tenacity) between 1.0 cN/dtex and 3.5 cN/dtex, and elongation between 40% and 100%. Tenacity is the breaking load in cN divided by the linear density of fiber. Heat treatment (activation) to melt the cover of these BiCo fibers was needed to form a bonded network between other fibers. Melting temperatures of the polyethylene sheath and polypropylene core were 130°C and 160°C, respectively.

#### Other foam-laid fibers

Polyvinyl alcohol (PVA) fibers were used as a thermoplastic fiber. The PVA fibers were VPB105-2/4 mm (1.2 dtex) with a length of 4 mm from Kuraray (Tokyo). Heat treatment (activation) to melt the cover of these PVA fibers was needed to form a bonded network between other fibers. The melting temperature was 130°C. Polylactic acid (PLA) fibers were “PLA type 400” (1.8 dtex) with a length of 4 mm from Trevira (Bobingen; Germany). Properties of the individual fibers were as follows: density 1.25 g/cm<sup>3</sup>, and tensile strength between 1.8 cN/dtex and 5.4 cN/dtex.

#### Foaming surfactants

The commercially available surfactant used as a reference foaming agent in this study was anionic sodium dodecyl sulfate (SDS) from Merck Chemicals (Darmstadt, Germany). The molecular weight of SDS (CH<sub>3</sub>(CH<sub>2</sub>)<sub>11</sub>SO<sub>4</sub>Na) is 288 g/mol. The surfactant is biodegradable. Sodium dodecyl sulfate is mentioned in the recommendation of the German Federal Institute for Risk Assessment (BfR) in the list of materials intended for food contact.

The CH-Polymers CHP 557 and CH-Polymers partly bio-raw-material-based latex CHP 5157.98 EP could act as foaming agents (CH-Polymers Oy; Raisio, Finland); therefore, SDS was not used with them. The CH Polymers CHP 557 and the CHP 5157.98 EP are anionic aqueous dispersion based on acrylic ester with a particle size of 0.5 µm and 0.18 µm, respectively.

Kuraray Poval 6-88 by Kuraray is a PVA having a varying degree of polymerization and hydrolysis. It is a water-soluble polymer manufactured by alcoholysis of polyvinyl acetate. It is notable for its good bonding strength and pigment binding capacity, because PVAs have such good cohesion and good adhesion to fibers, fillers, and pigments. The used PVA had known foaming performance [31].

#### Methods

##### Pilot paper machine

The pilot trials were run using the VTT SUORA pilot line in Jyväskylä, Finland, consisting of an approach system, a forming section (hybrid former), and a press section (one shoe nip) [25-26]. The schematic layout of the forming section of the SUORA pilot during the trials is presented in **Fig. 1a**. The web width during the trials at the forming section was 300 mm, and after trimming at the winder, it was 240 mm. The machine speed was 350 m/min and 250 m/min for water- and foam-laid forming, respectively. The jet-to-wire speed ratio was 0.99.

Softwood pulp was fed into the front chest at 1.5% consistency. Dry PVA and PLA fibers were fed in the front chest at the targeted ratio. The amounts of SDS, latex, bio-latex, and PVA were 1.3 g/L, 9.6 g/L, 6.2 g/L and, 2.0 g/L, respectively. Dewatering flows from the vacuum units at the forming section are connected to five separate weir collectors. The dewatering measurement from the forming section was based on pumps and flow meters. Dewatering flow rates were recorded. Additionally, samples from the headbox and web samples after the forming section were taken for consistency measurement. Wet pressing was carried out by applying a single shoe press. The liner load of the shoe press unit was constantly 1000 kN/m. Web solids content after the forming section in the foam-laid mode was typically between 35% and 40%.

The foam-laid web forming with the 4-mm PVA fibers

and latex caused some difficulties, which led to the rejection of this combination. Latex retention seemed to be reasonable for the strength properties. However, the air content of foam and water removal at the forming section with the combination of latex, PVA fiber, and BSK pulp was not adequate. Inadequate air content deteriorated the web formation, but an increase in latex amount would have led to difficulties with wastewater treatment.

## Pilot dryer machine

A separate pilot cylinder dryer was used for drying the rolls, as shown in Fig. 1b. The pilot cylinder dryer consisted of four steam-heated cylinders (diameter 1.2 m), four dryer fabric groups (width 660 mm), and an unwinding and reeling stage. The velocity of each dryer group was adjusted independently, as well as fabric tension and steam pressure in drying cylinders. An increasing temperature profile from 60°C to 127°C was used for cylinders. The moisture content of the web was measured before and after heating using MM-55 infrared (IR) modules. The target moisture content of the web was adjusted by controlling the machine speed (the maximum speed of the machine was 70 m/min). The applied wire tensions were from 0.6 kN/m to 0.7 kN/m to maximize cross-machine direction (CD) shrinkage. Typical operating tensions for most industrial paper machines are in the range of 2.1–3.2 kN/m [32]. The web tension was controlled between the unwinder and the first drying cylinder using a control system consisting of the unwinder with drive and a weighted roll. The web tension between the dryer cylinders was adjusted by controlling the speed differences between the cylinders and reeling. The speed difference over the whole dryer was negative, leading to overall MD drying shrinkage.

## Pilot in-plane compaction

Pilot scale compaction of the rolls was made by Gruppo X di X Gruppo srl (Venice, Italy). Their trademarked Papermorphosis pilot machine was applied to increase the extensibility of webs by the in-plane compaction method [33–34]. In this case, the process was optimized targeting the highest possible elongation in both MD and CD directions. However, the elongation of the two directions was not expected to be symmetrical. The evaluation addition to CD elongation was at a maximum of 8%, whereas the expectation was higher for MD elongation. One of the key factors for successful in-plane compaction was the solids content of paper [1]. After the in-plane compaction, the webs were dried to solids content between 92% and 93%.

## Heat activation method

The SutCo pilot machine at VTT was run in the opposite direction (from winder to unwinder) compared to the typical running direction [35] to run with low-web tension. The applied activation temperature was 140°C, web speed 1.0 m/min, and activation time 2.5 min.

## 3D forming method

The formability of the materials was evaluated with a series of 3D forming tests using a MiniMould tool (see [36] for a more detailed description of the method). The size of the MiniMould test tray was 90 mm x 80 mm x 35 mm (depth can be varied). The forming tool allows both fixed and sliding blank converting procedures. In the fixed blank procedure, the blank is not allowed to move during the forming process, and in the sliding blank procedure, the blank is allowed to move during the forming process. In the experiments, both were used: a fixed blank process and a sliding blank process with a high blank holding force that combines the straining and sliding of the blank. The tool temperatures for female mould and male mould were 160°C and 50°C, respectively. A blank holding force of 4.7 kN and between 0 to 0.8 kN were applied for fixed blank and sliding blank, respectively. The applied pressing force was 100 kN, pressing velocity 40 mm/s, and dwell time 500 ms. The sample materials were stored in humidity-controlled chambers at selected conditions to stabilize the moisture content of die-cut blanks. Storage of sample materials was performed at 80% relative humidity (RH) and 23°C temperature.

## Shrinkage

The amount of the total shrinkage of the sheets was influenced by partly unrestrained drying procedures and in-plane compaction. Elongation of shrunken paper in percentage units is presented according to Eq. 1:

$$\text{Elongation} = \frac{\Delta S + \epsilon_{\text{restrained}}}{100 - \Delta S} \quad (1)$$

where  $\Delta S$  is the shrinkage, i.e., the percentage length reduction of the sample (due to drying shrinkage, in-plane compaction, or creping operations); “100” refers to the length of the sample before the shrinkage; and  $\epsilon_{\text{restrained}}$  is the percentage elongation of a corresponding, completely restrained dried sheet. The background of this non-empirical equation is explained and empirically verified in [10]. In this study, the shrinkage process of paper rolls consisted of several phases. The CD shrinkage was determined by measuring the width of the sheets at the forming section and after all the events that generated shrinkage. The MD shrinkage was calculated using machine section speed differences at the dryer and by applying marker dots with known separations in the sheets at the in-plane compaction pilot. Separate shrinkage events can be connected for calculation (total) shrinkage using Eq. 2:

$$\Delta S = 100 \times \prod_{n=1}^p \frac{(100 - S_n)}{100} = 100 \times \frac{(100 - S_1)}{100} \times \frac{(100 - S_2)}{100} \times \dots \times \frac{(100 - S_p)}{100} \quad (2)$$

where  $S_n$  is the shrinkage of the sample in a single event that creates a certain length reduction, i.e., the percentage length reduction of the sample.

| Trial Point      | SW Content, % | 2nd Fiber Content, % | Foaming Agent | Air Content in Forming, % | Grammage, g/m <sup>2</sup> | Density, kg/m <sup>3</sup> | Drying Shrinkage (MD & CD), % | Elongation (MD & CD), % | MD Tensile Index, Nm/g  | MD/CD Tensile Ratio |
|------------------|---------------|----------------------|---------------|---------------------------|----------------------------|----------------------------|-------------------------------|-------------------------|-------------------------|---------------------|
| W3               | 100           | 0                    | -             | -                         | 139.4                      | 638                        | 0.12 & 3.3                    | 3.4 & 4.2               | 76.7 ± 6.0              | 2.3                 |
| W6 <sup>A</sup>  | 80            | BiCo 20              | -             | -                         | 141.0                      | 480                        | 0.76 & 3.8                    | 4.5 & 8.0               | 82.0 ± 6.0 <sup>B</sup> | 2.0 <sup>B</sup>    |
| W10 <sup>A</sup> | 70            | BiCo 30              | -             | -                         | 141.8                      | 315 <sup>B</sup>           | 1.41 & 2.5                    | 4.7 & 5.9 <sup>B</sup>  | 68.6 ± 6.1 <sup>B</sup> | 1.9 <sup>B</sup>    |
| F3               | 100           | 0                    | SDS           | 34.0%                     | 128.5                      | 668                        | 0.68 & 4.3                    | 2.7 & 4.6               | 103 ± 4                 | 3.6                 |
| F5 <sup>A</sup>  | 100           | 0                    | Latex         | 11.3%                     | 127.0                      | 608                        | 1.65 & 4.2                    | 3.8 & 3.5               | 104 ± 7                 | 3.7                 |
| F9 <sup>A</sup>  | 90            | PLA 10               | Bio-latex     | 15.9%                     | 135.7                      | 541                        | 1.60 & 4.2                    | 3.5 & 2.6               | 76 ± 5                  | 3.3                 |
| F10 <sup>A</sup> | 90            | PVA 10               | PVA           | 33.6%                     | 119.4                      | 630                        | 1.55 & 4.2                    | 4.3 & 6.7               | 114 ± 10                | 2.3                 |

SW: softwood; BiCo: polymeric bicomponent fibers with polyethylene cover and polypropylene core; PLA: polylactic acid; PVA: polyvinyl alcohol; SDS: sodium dodecyl sulfate.  
Machine direction (MD) drying shrinkage was controlled and calculated by machine draws.  
Cross-machine direction (CD) drying shrinkage was calculated using the web dimensions before and after drying.  
A: Heat activated in laboratory conditions at 140°C for 5 min before tensile testing.  
B: Parameters measured for a duplicate roll with identical material recipe and process conditions.

## II. Recipes and description of the materials after pilot machine drying.

### Tensile testing

Testing of the paper sheet samples took place at a temperature of 23°C and 50% RH. The thickness and apparent sheet density of the dry paper were measured using ISO 534:2011 “Paper and board — Determination of thickness, density and specific volume,” and air-dry basis weight was determined using ISO 536:2019 “Paper and board — Determination of grammage.” The samples with different shrinkage were also strained to failure using a strain rate of 100 mm/min in a Lloyd tensile tester, in accordance with ISO 1924-2:2008 “Paper and board — Determination of tensile properties — Part 2: Constant rate of elongation method (20 mm/min).”

## RESULTS

### Pilot-machine-made paper web

#### Paper webs

The recipes, and some of the properties, of the manufactured pilot rolls are presented in **Table II**. The basis weight targets of the water and foam-laid rolls were 140 g/m<sup>2</sup> and 130 g/m<sup>2</sup>, respectively. The samples containing thermoplastic components were heat activated in laboratory conditions at 140°C for 5 min before tensile testing. The purpose of the heat activation was to melt polymeric components and increase bonding between the polymeric materials and cellulose fibers. As shown in Table II, tensile strength was sometimes increased or decreased compared to 100% cellulose references due to heat treatment, depending on the polymeric material grade and material combinations. The effectiveness of heat activation also depends on the temperature and time; temperature that is too high may destroy the polymeric fibers, and temperature that is too low and at short time may cause no effect.

All the presented rolls were in-plane compacted later using a pilot machine. The air content of the foam-laid trial points with SDS and PVA as surfactants were relatively low (compare, for example, [31]), but despite that visual formation and visual web quality, quality of the webs was acceptably good. However, the foaming ability and water removal at the forming section, with the combination of the used latexes, PVA fiber, and refined kraft, were not adequate. Inadequate air content of the foam-laid trial points with latex and bio-latex deteriorated the web formation, and the increased addition of latex would have led to difficulties with wastewater treatment. The problems at the forming section of the pilot machine indicated that the foaming performance of the used latexes should have been significantly better. The latex dosage in these pilot trials was remarkably lower compared to the prior laboratory study [16].

#### Elongation of paper webs

Drying shrinkage and elongation in MD and CD were similar in water- and foam-laid papers. Drying shrinkage was from 0.12% to 1.65% in MD and from 2.5% to 4.3% in CD. The elongation was from 2.7% to 4.7% in MD and from 3.5% to 8.0% in CD. The BiCo fiber and PVA fibers slightly improved elongation compared to the BSK references.

#### Strength of paper webs

The tensile index in MD of the foam-laid materials was systematically higher compared to water-laid materials (Table II). The tensile index in MD varied from 69 Nm/g to 114 Nm/g, and three foam-laid materials reached over a 100 Nm/g tensile index. The tensile index in CD was typically from 25 Nm/g to 35 Nm/g (except for F10 samples, with the upper range at 49 N/mg). The tensile index ratios

| Trial Point | Solids at Compaction, % | Initial Basis Weight, g/m <sup>2</sup> | Final Basis Weight, g/m <sup>2</sup> | Density, kg/m <sup>3</sup> | Measured Compaction, % | Measured Shrinkage, % | Final Roll Length, m |
|-------------|-------------------------|----------------------------------------|--------------------------------------|----------------------------|------------------------|-----------------------|----------------------|
| W3          | 70                      | 139                                    | 178                                  | 488                        | 23                     | -                     | 450                  |
| W6          | 71–72                   | 141                                    | 164                                  | 390                        | 23.5                   | -                     | 500                  |
| W10         | 79–82                   | 142                                    | 163                                  | 391                        | 15–16                  | -                     | 200                  |
| F3          | 74                      | 129                                    | 205                                  | 454                        | 31.5                   | 32.9                  | 387                  |
| F5          | 72                      | 127                                    | 193                                  | 445                        | 32                     | 34.2                  | 315                  |
| F9          | 74                      | 136                                    | 202                                  | 436                        | 31                     | 32.3                  | 400                  |
| F10         | 74                      | 120                                    | 180                                  | 475                        | 32                     | 33.9                  | 400                  |

### III. Material parameters related to in-plane compaction.

presented in Table II were typically 0.5–1 unit higher after pilot drying compared to restrained laboratory drying. The tensile index of the laboratory drum-dried samples was significantly lower in MD, but the CD was at a similar level compared to pilot-dried samples. The tensile index of some commercial paper grades varies from 25 to 50 Nm/g in CD and 50 to 100 Nm/g in MD [18], but the values can also be significantly higher for oriented papers [37].

The original hypothesis was that various long stable fibers (> 4 mm) could strengthen the paper structure against local rupturing during an elongation event. However, in our prior unpublished studies, long fibers did not typically improve elongation, but as shown in [16], PVA fibers gave a reasonable response. A likely explanation for poor strengthening performance could be the limited bonding of the long fibers with cellulose fibers. The PVA fiber surfaces likely melted during drying, thus they likely bonded to cellulose fibers, as in sample F10.

#### Tensile properties of air-dried samples

The comparison between the samples air-dried at SutCo and the pilot-cylinder-dried F3 reveals that air drying improved CD elongation by between 2% and 3% units and MD elongation by between 1% and 1.5% units. The tensile index was slightly higher after the pilot cylinder drying. SutCo presents unrestrained drying compared to the pilot cylinder dryer, though the draws during the cylinder drying were minimal. All the samples had MD shrinkage between 0% and 2.1%, and most of the samples had CD shrinkage between 3.8% and 8%. The elongation performance of the air-dried samples in CD was lower than expected. Web shrinkage usually concentrates on the edges. However, the samples for the CD tensile measurement were taken on the center area of the web, which may explain the lower elongation.

#### *In-plane compaction*

##### In-plane compaction

The solids content of all the delivered rolls was approximately between 8% and 10% after drying, so there was a

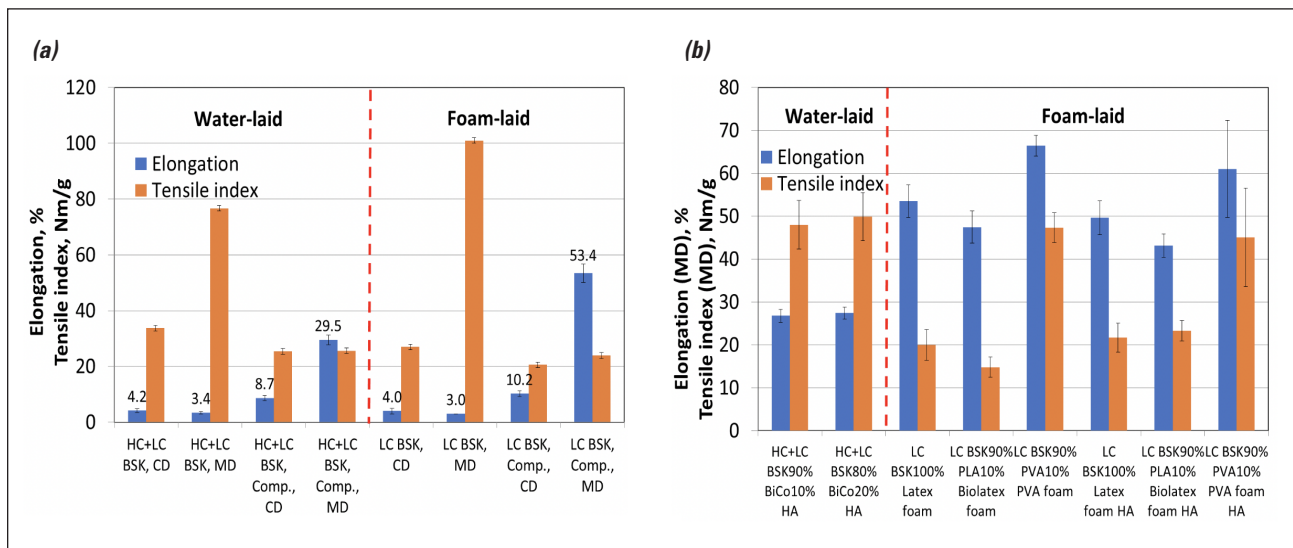
need for remoisturizing the rolls. Moisture was added from one side of the roll. The W3, F3, F5, and F10 presented in **Table III** had excellent water-absorbing properties, whereas online moisturization of W6, W10, and F9 was difficult. The foam-laid rolls were remoisturized at solids contents between 72% and 74%, at an intensity of compacting of 30% at a speed of 6.7 m/min and with a final dry content of 94%. The water-laid materials were re-moisturized at solids content between 70% and 82%, and intensity of compacting varied between 15% and 23.5%. In-plane compaction of the foam-laid materials resulted in approximately 10 percentage units higher value compared to the water-laid materials. The compaction amount in MD was detected from machine data. A tool was used to create red spots before compaction with a rotating device having a revolution of 100 cm. The distance between two red spots can be used to confirm the compaction performance. A slight variation was found between machine data for compacting intensity and measured distances, but the origin of the difference remained unclear.

#### Density and basis weight of the materials

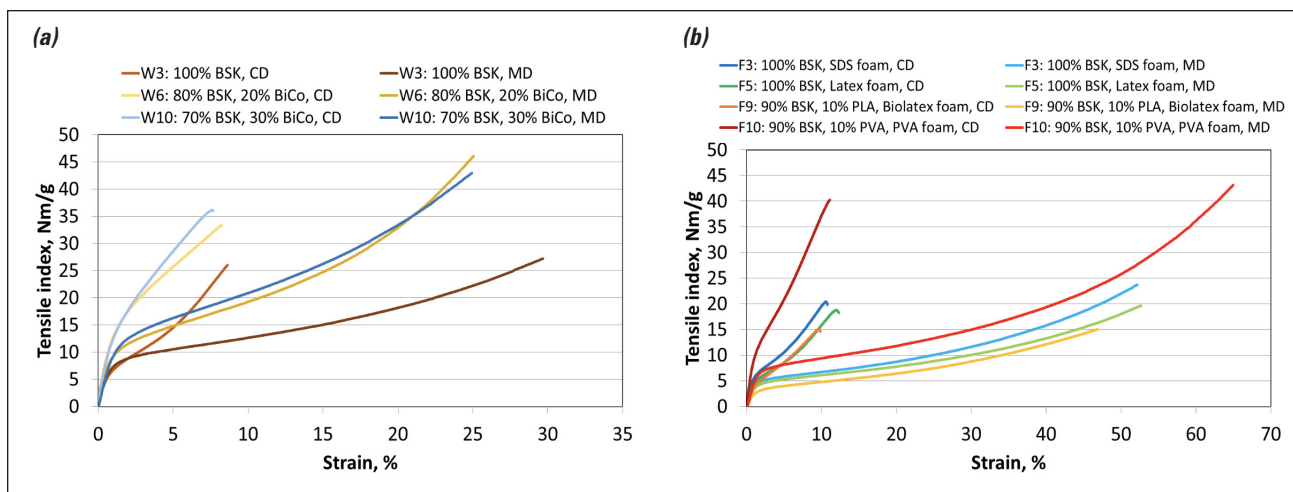
After in-plane compaction, the apparent basis weight of all the materials was increased, whereas the density of the materials was decreased (with W10 with 30% BiCo fiber as the only exception). The density of the foam-laid materials decreased more compared to water-laid materials. The decrease of density in the 100% BSK materials W3 and F3 was larger compared to other water- and foam-laid materials, respectively.

#### Tensile properties

Elongation and tensile index of 100% BSK-based water-laid (W3) and foam-laid (F3) samples are presented in **Fig. 2b**. Elongation before the pilot compaction in MD and CD was from 3% to 4% as shown previously in Table II. After the pilot compaction, elongation in CD was from 9% to 10%, and in MD from 29.5% to 53.4% for the water-laid (W3) and foam-laid (F3) samples, respectively. The



**2. Elongation and tensile index of: a) 100% bleached softwood kraft (BSK) pulp samples with sodium dodecyl sulfate (SDS) as foaming surfactant; and b) in-plane compacted BSK-based samples with thermoplastic additives (CD: cross-machine direction; MD: machine direction; HA: heat activated). Fibers used were polylactic acid (PLA); polyvinyl alcohol (PVA); and a polymeric bicomponent fiber with polyethylene and polypropylene (BiCo). Foaming surfactants used were latex, bio-latex, and PVA.**



**3. Tensile index – elongation curves of in-plane compacted samples: a) water-laid (W), heat-activated (HA) pilot samples; and b) foam-laid (F), not heat-activated pilot samples.**

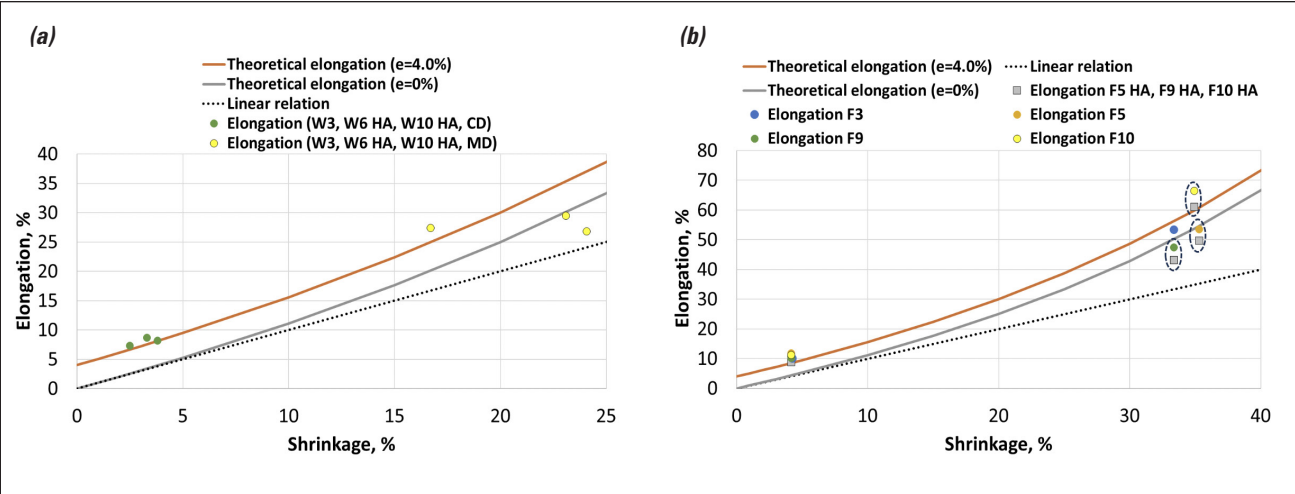
tensile index in MD deteriorated due to the in-plane compaction from 80 Nm/g to 100 Nm/g to around level 25 Nm/g. Elongation of the foam-laid, in-plane compacted samples containing thermoplastic components before heat activation (F5, F9, and F10) in MD was 53.6%, 47.5%, and 66.4%, respectively. Heat activation treatment decreased elongation in MD between 3.9 and 5.4 percentage points and elongation in CD between 1.0 and 2.5 percentage points. In CD, the elongation values of water-laid and foam-laid materials were between 7.3% and 8.7% and between 10.2% and 11.8%, respectively. However, the heat activation increased tensile strength both in CD and in MD. Additionally, the water-laid BiCo fiber and foam-laid PVA-containing samples had an MD tensile index between 45 Nm/g and 50 Nm/g after in-plane compaction.

### Tensile curves

The tensile index elongation curves of the in-plane compacted activated samples are presented in **Fig. 3a–3b**. Curves of the MD compacted samples were concave upward, which was the expected shape [38]. Shapes of the MD curves of all foam-laid materials were similar, but the sample F10 broke later compared to the others, which indicates increased fiber bond strength, increased number of bonds, or both [12].

### Relationship between shrinkage and elongation

Elongation in MD and CD as a function of shrinkage for the pilot materials is presented in **Fig. 4a–4b**. Shrinkages of the in-plane pilot-compacted, foam-laid samples in MD, shown in Table III, were high (above 30%), which explained



4. Elongation as a function of shrinkage for: a) water-laid (W); and b) foam-laid (F) pilot-manufactured samples. Compaction and heat activation (HA) were performed at the pilot machine. Theoretical elongation is calculated according to Eq. 1.

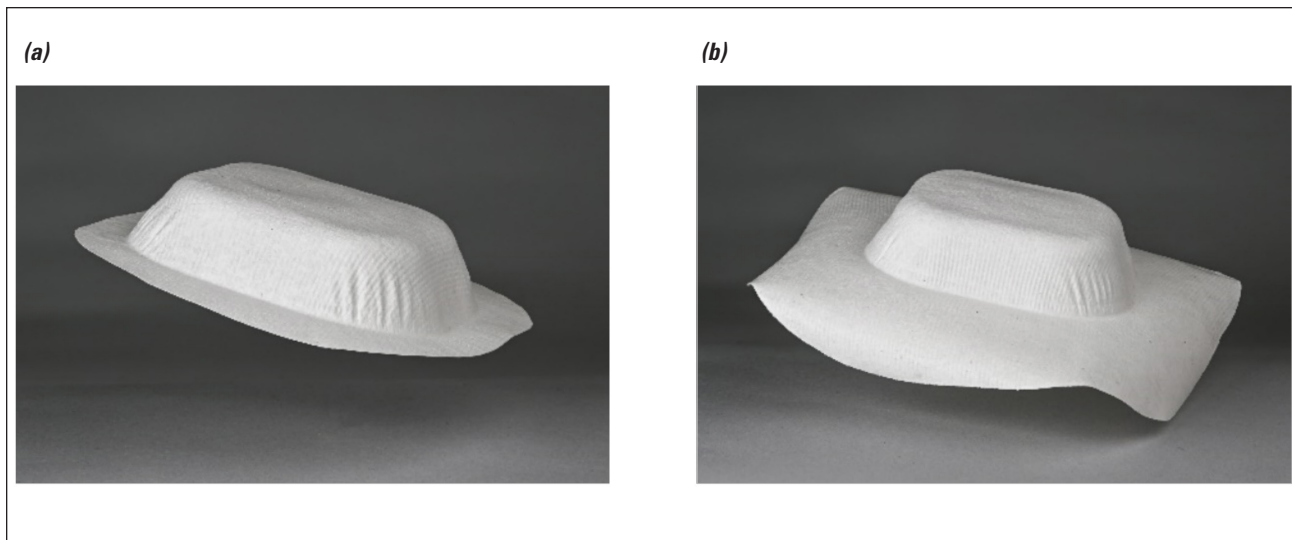
the very high elongation values (Fig. 4b). In-plane pilot compaction of the water-laid materials led to clearly lower elongation values compared to the foam-laid results (Table III). The experimental results followed the trend of the theoretical elongation that was calculated according to Eq. 1 (Fig. 4a–4b). The difference between the experimental data and the linear relation became visible at higher shrinkage in Fig. 4b. The variation of the experimental data around the theoretical elongation possibly originated partly from the varying tensile strength of the materials and partly from some details related to shrinkage detection of the materials. At the least, materials with a relatively low

tensile strength usually cannot reach the theoretical elongation [10]. On the other hand, the role of viscoelastic strain recovery on the shrinkage in multi-step in-plane compression cases may be significant [39]. The heat activation decreased the elongation values by several percentage points; the sample pairs are indicated with circles in Fig. 4. The results show that PVA fiber and surfactant were beneficial for shrinkage in compaction and improved elongation of the material. Another key observation was that the good formation of the foam-formed paper web likely improved the effectiveness of the in-plane compaction process. The dimensions of PVA fibers could be such that they did not

| Trial Point | Moisture Content Before 3D Forming, % | Maximum Fixed Blank Forming Depth, mm | Maximum Depth in Sliding Blank, mm | Maximum Blank Holding Force in Sliding Blank, kN |
|-------------|---------------------------------------|---------------------------------------|------------------------------------|--------------------------------------------------|
| W3 HA       | -                                     | 15.0                                  | 20                                 | 0.8                                              |
| W6 HA       | -                                     | 13.0 (B 14.5)                         | 20                                 | 0.8                                              |
| W10 HA      | -                                     | 13.5 (B 14.5)                         | 20                                 | 0.8                                              |
| F3          | 7.5                                   | 13.5                                  | 30                                 | 0                                                |
| F5 HA       | 7.2                                   | 14.0                                  | 35                                 | 0.08                                             |
| F5          | 7.9                                   | 14.0                                  | 35                                 | 0.08                                             |
| F9 HA       | 7.2                                   | 14.0                                  | 35                                 | 0.08                                             |
| F9          | 8.2                                   | 13.0                                  | 35                                 | 0.08                                             |
| F10 HA      | 7.4                                   | 20.0                                  | 35                                 | 0.79                                             |
| F10         | 8.7                                   | 19.5                                  | 35                                 | 0.63                                             |

HA: Heat-activated sample.  
B: The temperature of the female mould was 120°C.  
In all other cases, the temperature was 160°C.

IV. Three-dimensional (3D) forming performance of the water- and foam-laid materials.



**5. Maximum forming depth for F10 was: a) 20 mm for heat activated, and b) 19.5 mm for not heat activated.**

influence the formation of the paper web. A recipe containing PVA as a foaming agent without PVA fiber can likely be successful, despite in-plane compaction performance that was not tested in this study due to limited resources.

### 3D forming

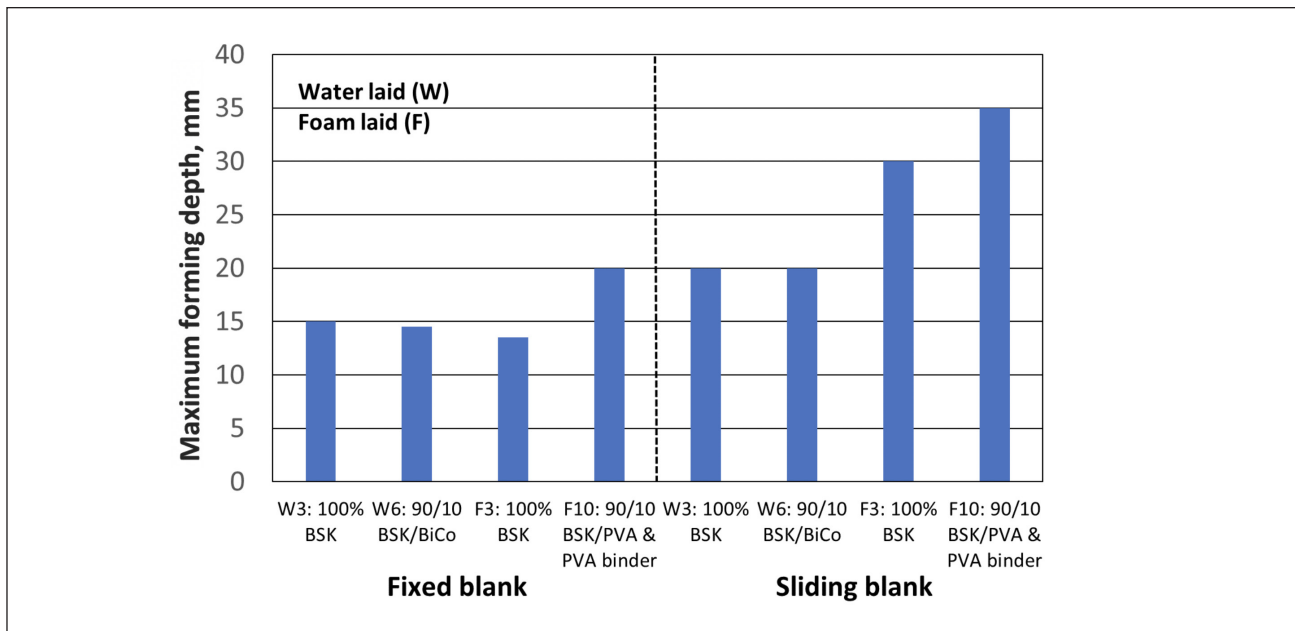
The performance of the materials in different forming conditions was tested using the fixed and sliding blank tests applying the MiniMould geometry [36]. The greatest forming depths were achieved (with a small difference of ~0.5 mm of depth) as the CD of the sheets was parallel to the long side of the MiniMould forming tool. The maximum forming depths of the fixed and sliding blank 3D-formed samples and maximum blank holding forces in sliding blank are shown in **Table IV**. The moisture content of the foam-laid samples before forming varied from 7.2% to 8.7% (Table IV). The foam-laid samples that were not heat activated had approximately 0.7% to 1.3% higher moisture content compared to the activated samples. Additional moistening by spraying the sheets (tray blanks) was tested after storage of sample materials at 23°C and 80% RH. However, increased moisture content weakened the fiber structure; therefore, the method was not applied systematically for all samples. Related to the same MiniMould forming tool, Berthold et al. have reported optimized blank moisturization around the 12% level to improve paperboard press-forming performance at a sliding blank setup [40].

In fixed blank forming, sample F10 (90% BSK pulp, 10% PVA fiber, and PVA as foaming chemical) reached the maximum forming depth of 20 mm and 19.5 mm with heat activation (HA) and without HA, respectively (**Fig. 5**). All the other water and foam-laid materials reached a lower maximum forming depth between 13.0 mm and 15.0 mm (Table IV). The foam-laid materials F5, F9, and F10 — with and without HA — achieved 35-mm forming depth when the blanks were allowed to slide (35 mm was the maximum for

the MiniMould tool). The maximum forming depth for water-laid samples using the sliding blank test was 20 mm, which was 15 mm less compared to the depth of the best foam-laid samples (**Fig. 6**). The criteria for the maximum forming depth in sliding blank forming was that excessive wrinkles were not allowed and that the potential sealing surface (tray flange) could be called flat. Tanninen et al. [41,42] investigated the composition and essential dimensions of crease-assisted folds at tray flange corners, which can be used to assess acceptable dimensions for the randomly generated wrinkles. The wrinkle formation in complex friction conditions in a sliding blank process is related to pressure in the thickness direction of the material [43]. Some folds in the tray walls appeared, but they were considered acceptable (**Fig. 7**). The edges of the sliding blank-formed materials were relatively smooth.

The blank holding force used for the foam-laid sample was optimized for the maximum forming depth (Table IV). The highest blank holding force, 0.79 kN, was used for the sample F10 HA, whereas no force could be used with F3 (100% BSK pulp and SDS as a surfactant) and only a 30-mm depth could be formed. The blank holding force used for the water-laid samples was not optimized and was fixed to 0.8 kN, which may have slightly limited the maximum depth. The metal-to-paper friction plays an important role in paperboard press-forming performance in a sliding blank setup [40]. However, the results indicate that the PVA component as foaming agent and as a fiber was beneficial for the maximal performance of F10 (90% BSK pulp, 10% PVA fiber, and PVA as foaming chemical). Heat-activated materials performed slightly better in the 3D forming test with the MiniMould tool.

The good performance of the foam-laid materials was based on a combination of technology (machinery), foaming additives, and fibers. In this study, machinery was fixed, and therefore, performance differences between the foam-laid materials was likely related to the chemistry used and



**6. The maximum forming depth of in-plane compacted pilot samples in fixed and sliding blank 3D forming using the MiniMould tool. The samples W3 and F3 consisted of 100% BSK, and the heat-activated samples W6 and F10 contained thermoplastic components.**

long fibers. The advantages of foam-laid forming technology to paper properties have been presented in the literature [22-30]. However, the key structural mechanisms improving shrinkage and elongation need further investigation after this conceptual study. The application of the foam-laid papermaking process can be beneficial in many ways. Lehmonen et al. [25] reported enhancement in dewatering as a function of decreasing density of the flowing media after the forming section and wet pressing solids content after the press section. The results indicated that solids content levels can be improved when the fluid density is at the lowest level with foam forming technology. The results enable drying energy savings in the papermaking process.

## CONCLUSION

The complete production chain concept, from pulp refining to 3D dry forming of shapes, was successfully proved using pilot-scale machinery. The best-performing material combination was the foam-laid LC refined bleached softwood kraft (BSK) pulp-based materials with thermoplastic PVA as a foaming agent and PVA fiber components. Compared to water-laid formed materials, competitive material extensibility and 3D forming performance can be reached with foam-laid web forming using SDS and likely PVA as a foaming agent, without synthetic fiber addition.

Renovation of a water-laid paper machine process to a foam-laid process is doable without a complete rebuild. There are also in-plane compaction units on current production machines. Certainly, the in-plane compaction phase for high extensibility needs to be optimized well, and conceptually it seems possible according to these results. The PVA should be collected from wastewater to make the

foam-laid process affordable, but the required modifications to the process can be arranged. The results suggest that offline HA treatment is not necessary for PVA, which is beneficial for the success of the whole process. Based on these considerations, a highly extensible paper material for dry 3D forming applications can be produced on a mill scale if one successfully combines a foam-forming paper machine and an in-plane compactor machine.

The key conclusion related to this investigation was that the dry 3D forming performance of the best foam-laid material was significantly better compared to water-laid formed materials. The difference can be detected in the forming depths of the fixed and sliding blank and the smoothness of the edge area. Heat activation of polymeric-additives-containing materials improved dry 3D forming performance, though elongation of materials was slightly decreased. On the other hand, heat activation improved the tensile strength of materials. The results support findings that the key material properties for dry 3D forming applications include at least an optimal combination of high extensibility and high tensile strength. However, the key underlying mechanisms explaining the success of foam-laid materials compared to water-laid materials could not be investigated thoroughly due to limited time and resources. Therefore, systematic explanations could not be given. Further investigation of these underlying mechanisms is needed.

The results show that highly anisotropic paper material with very high elongation in one direction (up to 66.4% in MD and around 10% in CD) can have good dry 3D forming performance. The MD elongation of pilot-machine-produced paper material was well above what is needed for



7. Maximum forming depth (35 mm) was prepared using sliding blank forming with the MiniMould tool.

industrial and commercial applications. However, a reasonable additional increase of the CD elongation could be the last missing element enabling industrially fully competitive dry 3D forming performance of paper compared to plastic materials. In further investigations, the role of barrier properties and recyclability of materials need to be clarified in combination with high elongation.

In-plane compaction was the major factor in improving the elongation. In all foam-laid trial points, excellent compaction results between 31% and 32% were reached in MD, whereas the water-laid materials reached approximately 10-percentage-unit lower compaction results. Elongation as a function of shrinkage followed the trend of the theoretical relationship presented in the literature, which explained mostly a 30% elongation level for the water-laid and between 50% and 66% elongation for the foam-laid materials.

The role of applied polymeric foaming agents was significant for the whole. The results show that PVA as a foaming agent improved the elongation and tensile strength and that the pilot paper machine operation with the PVA was straightforward. Latex and bio-latex were not found to raise tensile strength as expected, partly due to their inadequate dosages, which were limited by the wastewater treatment limitations at the pilot paper machine. The inadequate latex dosages lead to low air content during the forming process. Despite the low air contents, the experimental materials with latexes performed relatively well in the tensile tests. Further investigations targeting excellent 3D forming performance of paper could focus on improving the foaming ability of latex and the optimal performance of PVA as a surfactant and strength additive. **TJ**

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## LITERATURE CITED

1. Vishtal, A., "Formability of paper and its improvement," Ph.D. dissertation, Tampere University of Technology, Tampere, Finland, 2015.
2. Vishtal, A. and Retulainen, E., *BioResources* 9(4): 7951(2014). <https://doi.org/10.15376/9.4.7951-8001>.
3. Seth, R.S., *Pulp Pap. Mag. Can.* 106(2):33(2005).
4. Lindström, T., Wågberg, L., and Larsson, T., "On the nature of joint strength in paper – A review of dry and wet strength resins used in paper manufacturing," in *Advances in Paper Science and Technology, Trans. of the XIIIth Fund. Res. Symp.* (S.J. l'Anson, Ed.), Cambridge, 2005, pp. 457-562, FRC, Manchester, 2018. <https://doi.org/10.15376/frc.2005.1.457>.
5. Hubbe, M.A. *BioResources* 9(1): 1634(2014). <https://doi.org/10.15376/biores.9.2.1828-1829>.
6. Zeng, X., Vishtal, A., Retulainen, E., et al., *BioResources* 8(1): 472(2013). <https://doi.org/10.15376/biores.8.1.472-486>.
7. Khakalo, A., Vishtal, A., Retulainen, E., et al., *Cellulose* 24: 191(2017). <https://doi.org/10.1007/s10570-016-1102-z>.
8. Khakalo, A., Kouko, J., Filpponen, I., et al., *ACS Sustainable Chem. Eng.* 5(10): 9114(2017). <https://doi.org/10.1021/acssuschemeng.7b02025>.
9. Östlund, S., "Three-dimensional deformation and damage mechanisms in forming of advanced structures in paper," in *Advances in Pulp and Paper Research, Trans. of the XVIth Fund. Res. Symp.* (W. Batchelor and D. Söderberg, Eds.), Oxford, 2017, pp. 489-594, FRC, Manchester, 2018. <https://doi.org/10.15376/frc.2017.2.489>.
10. Kouko, J. and Retulainen, E., *Nord. Pulp Pap. Res. J.* 33(3): 522(2018). <https://doi.org/10.1515/npprj-2018-3057>.
11. Ketola, A.E., Strand, A., Sundberg, A., et al., *BioResources* 13(3): 5319(2018). <https://doi.org/10.15376/biores.13.3.5319-5342>.
12. Kouko, J., Turpeinen, T., Kulachenko, A., et al., *TAPPI J.* 19(3): 125(2020). <https://doi.org/10.32964/TJ19.3.125>.
13. Laukala, T., Tanninen, P., Aghamohammadi, G., et al., *Cellulose* 30: 1449(2023). <https://doi.org/10.1007/s10570-022-04984-x>.
14. Marin, G., "Impact of paperboard deformation and damage mechanisms on packaging performance," Ph.D. dissertation, KTH Royal Institute of Technology, Stockholm, 2023.
15. Salminen, K., Lappalainen, T., Hjelt, T., et al., "Formable cellulose-based webs enabled by foam forming technology," *PaperCon*, TAPPI Press, Peachtree Corners, GA, USA, 2023.
16. Kouko, J., Tanninen, P., Leminen, V., et al., *Cellulose* 31: 6955(2024). <https://doi.org/10.1007/s10570-024-06011-7>.

17. Niskanen, K. and Kärenlampi, P., in *Paper Physics* (K. Niskanen, Ed.), 1998, pp. 138-191.
18. Kouko, J., Kankkunen, T., Palmu, M., et al., *Materialia* 31: 101871(2023). <https://doi.org/10.1016/j.mtla.2023.101871>.
19. Park, N.Y., Ko, Y.C., Melani, L., et al., *Nord. Pulp Pap. Res. J.* 35(1): 61(2020). <https://doi.org/10.1515/npprj-2019-0052>.
20. Ihrman, C.B. and Öhrn, O.E., "Extensible paper by the double-roll compacting process," in *Consolidation of the Paper Web, Trans. of the 11th Fund. Res. Symp.* (F. Bolam, Ed.), Cambridge, 1965, pp. 410-434, FRC, Manchester, 2018. <https://doi.org/10.15376/frc.1965.1.410>.
21. Cluett, S.L., U.S. pat. 2,624,245 (Jan. 6, 1953).
22. Radvan, B. and Gatward, A.P.J., *Tappi* 55(5): 748(1972).
23. Smith, M.K., Punton, V.W., and Rixon, A.G., *Tappi* 57(1):107(1974).
24. Punton, V.W., in *Foams: Proceedings of a Symposium Organized by the Society of Chemical Industry* (R.J. Akers, Ed.), Academic Press, Cambridge, MA, USA, 1975, pp. 179-193.
25. Lehmonen, J., Rantanen, T., and Kinnunen-Raudaskoski, K., *TAPPI J.* 18(8): 461(2019). <https://doi.org/10.32964/TJ18.8.461>.
26. Kiiskinen, H., Salminen, K., Lappalainen, T., et al., *TAPPI J.* 18(8): 499(2019). <https://doi.org/10.32964/TJ18.8.499>.
27. Lehmonen, J., Jetsu, P., Kinnunen, K., et al., *Nord. Pulp Pap. Res. J.* 28(3): 392(2013). <https://doi.org/10.3183/npprj-2013-28-03-p392-398>.
28. Nikinmaa, M.S., "Wet-lay of synthetic fibers with complex fluids," Ph.D. dissertation, North Carolina State University, Raleigh, NC, USA, 2018.
29. Koponen, A., Torvinen, K., Jäsberg, A., et al., *Nord. Pulp Pap. Res. J.* 31(2): 239(2016) <https://doi.org/10.3183/npprj-2016-31-02-p239-247>.
30. Hjelt, T., Ketoja, J.A., Kiiskinen, H., et al., *J. Dispersion Sci. Technol.* 43(10):1462(2020) <https://doi.org/10.1080/01932691.2020.1869035>.

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31. Gottberg, J.M., Lappalainen, T., Salminen, K., *TAPPI J.* 18(8): 476(2019). <https://doi.org/10.32964/TJ18.8.475>.
32. Stenström, S., *Drying Technol.* 38(7): 825(2019). <https://doi.org/10.1080/07373937.2019.1596949>.
33. Sterner, M. and Magnusson, M., *TAPPI J.* 16(11): 633(2017). <https://doi.org/10.32964/TJ16.11.633>.
34. Trani, G., Sterner, M., and Cariolaro, F., WIPO pat. WO2005100686A1 (Oct. 27, 2005).
35. Kunnari, V., Kokko, A., Erho, T., et al., "Creating functionality on paper using novel roll to roll surface treatment equipment: Case studies," *PaperCon*, TAPPI Press, Atlanta, 2011.
36. Tanninen, P., Ovaska, S.S., Matthews, S., et al., *BioResources* 12(2): 3030(2017). <https://doi.org/10.15376/biores.12.2.3030-3042>.

## ABOUT THE AUTHORS

This paper presents a pilot-scale procedure for the production of a highly extensible paper web that is applicable to 3D forming. The key objectives of this investigation were to develop a material recipe, a pilot-scale manufacturing concept, and a demonstration of the competitive performance of a dry paper web in 3D forming. Previously, we had studied the subject extensively at laboratory scale.

The poor foaming performance of the latex grades used was the most surprising aspect during the pilot trials. We needed to replace latex with polyvinyl alcohol (PVA) as a surfactant, which was known to have reasonable foaming performance at pilot scale with a reasonable dosage.

We learned that foam forming can significantly improve the extensibility and the performance of a paper web material in the 3D forming of shapes compared to water-laid forming. Our key findings were that we can create highly extensible materials at pilot scale using only wood fibers and then boost the performance with additives.

Currently, foam-forming technology can be implemented on an existing paper machine. The research here could benefit mills by helping them create and manufacture new sustainable 3D formable wood-fiber-based materials for packaging applications that are competitive with plastic materials. Our next goal is to help companies develop their tailored optimized manufacturing concepts at mill scale.

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37. Niskanen, K., Sirviö, J., Wathén, R., in *Advances in Paper Science and Technology. Trans. XIIIth Fund. Res. Symp.* (S.J. l'Anson, Ed.), Cambridge, 2005, pp. 563-611.
38. Welsh, H.S., in *Consolidation of the Paper Web, Trans. IIIrd Fund. Res. Symp.* (F. Bolam, Ed.), Cambridge, 1966, pp. 397-409.
39. Skowronski, J. and Robertson, A.A., *J. Pulp Pap. Sci.* 12(1): 20(1986).
40. Berthold, L., Niini, A., Tanninen, P., et al., *BioResources* 19(2): 2272(2024). <https://doi.org/10.15376/biores.19.2.2272-2285>.
41. Tanninen, P., Leminen, V., Eskelinen, H., et al., *BioResources* 10(3): 5191(2015). <https://doi.org/10.15376/biores.10.3.5191-5202>.
42. Tanninen, P., "Press forming of paperboard – advancement of converting tools and process control," Ph.D. dissertation, LUT University, Lappeenranta, Finland, 2015.
43. Sanjon, C.W., Leng, Y., Yan, Y., et al., *Materials* 17: 4177(2024). <https://doi.org/10.3390/ma17174177>.



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