

Polyvinyl alcohol as foaming agent in foam formed paper

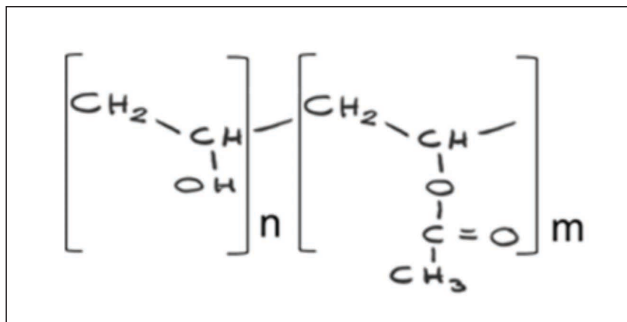
JENS-MIKAEL GOTTBORG, TIMO LAPPALAINEN,
AND KRISTIAN SALMINEN

ABSTRACT: The use of polyvinyl alcohol (PVOH or PVA) as a foaming agent in foam formed paper was investigated. Polyvinyl alcohol is a linear, nonionic water-soluble polymer. It has hydrophobic and hydrophilic parts that give it a surface-active character. PVOH is mainly characterized by degree of hydrolysis and molar mass. Degree of hydrolysis is given as mol-% hydroxyl groups on the polymer. Molar mass is measured indirectly by measuring the viscosity of a 4% PVOH solution. The results show that the degree of hydrolysis of PVOH had a strong effect on the foamability of PVOH. Foamability decreased strongly when the degree of hydrolysis increased from 88 to 98 mol-%. The effect of molar mass on foamability was weaker. We saw an increase in foam stability and bubble size with increasing molar mass, but we did not see any effect on maximum air content. PVOH dosage needed to reach >70% air content (Φ) varied from 2 g/l up to 10.5 g/l, and the lowest addition levels of PVOH needed were achieved with a low molar mass PVOH with a low degree of hydrolysis. The best strength properties were achieved when using fully hydrolyzed PVOH as the foaming agent. Strength properties (both in- and out-of-plane) of samples made using PVOH were better than those made using an anionic foaming agent (sodium dodecyl sulfate, SDS). By adding PVOH binder fibers to the pulp, we were able to further enhance the strength properties of paper and board.

Application: The use of polyvinyl alcohol as a foaming and strength agent has been investigated. The results can be used to judge which type of PVOH should be used when looking for optimum strength and foaming properties.

A fiber-foam mixture can be generated by introducing a foaming agent to the pulp suspension followed by intensive mixing or injection of air. An ideal foaming agent for foam formed paper or board should give rapid production of foam [1,2]. It should give the needed air content (Φ), and the bubble size should be small enough. This means a bubble radius below 100 μm . The ideal foaming agent should also be cost-efficient. Here, not only the price of the foaming agent should be considered, but also the total process cost. It is also important that the foaming agent should not have harmful interactions with other process chemicals. Ideally, the perfect foaming agent should also give additional functionality to the foam formed product. These could be properties like wet or dry strength or porosity of paper, to name but a few. This study aimed to assess the impact of properties of PVOH on fiber-foam characteristics and final product performance.

Polyvinyl alcohol (PVOH or PVA) is a water-soluble polymer that is a foamable, linear, and nonionic (**Fig. 1**). It has hydrophobic and hydrophilic parts that give it its surface-active character. PVOH is biodegradable in aqueous solutions [3] and also a strong binder. According to Miller et al., it is 3 to 4 times stronger than starch and 2 to 3 times stronger than acrylic or PVAc-based latex [4,5]. PVOH with a viscosity higher than 5 mPas has food contact approval for dry, aqueous, and fatty food according to the United States Food and Drug Administration (FDA) (§176.170 and §176.180) [6] and German BfR (XXXVI)[7]. PVOH is already widely used in the paper



1. Chemical structure of polyvinyl alcohol (PVOH). Due to incomplete saponification, the PVOH chain contains, in addition to hydroxyl groups (-OH), some acetate groups (-OCOCH₃).

industry, and it has found use in graphical paper, thermal paper, inkjet paper, tissue, and release paper, due to its high strength, good film-forming, and grease and oil barrier properties [4]. It has also been reported that PVOH has been used in papermaking as a dry strength additive [8] and that fully hydrolyzed polyvinyl alcohol (PVOH) is a polymer with good bonding properties [9]. It is also known that significant improvement in dry and wet tensile strengths have been detected when using fully hydrolyzed, cationic PVOH as a wet-end additive.

PVOH is produced in a two-step process. In the first step, vinyl acetate monomer is polymerized to polyvinyl acetate by radical polymerization. In this step, the molar mass of PVOH is decided. The molar mass can be adjusted by initiator type

and amount, as well as reaction conditions. Methanol is used as solvent and chain transfer agent in the production of PVOH [5,10]. Properties influenced by molar mass (M) are, among other things, viscosity in solution, strength, solubility, and drying speed. Lower molar mass will give a lower viscosity to PVOH in solution and vice versa a higher molar mass will give a higher solution viscosity. Higher molar mass will also give higher strength properties, and lower molar mass will give increasing solubility in water. Molar mass is generally expressed in terms of viscosity of a 4% solution of PVOH in water, because the measurement of molar mass of PVOH is complicated and the results are dependent on the measurement method used. The molar mass (M) of PVOH usually varies between 15000 g/mol and 250000 g/mol [11]; therefore, it is much larger than that of small anionic surfactants (e.g., M of sodium dodecyl sulfate is about 288 g/mol).

In the second step, polyvinyl acetate is saponified to PVOH. By varying process parameters like caustic content, reaction time, and temperature, the degree of hydrolysis can be varied [5,10]. The degree of hydrolysis is the amount of acetate groups that have been hydrolyzed to alcohol groups. The degree of hydrolysis is given as mol-%. It is generally said that the degree of hydrolysis of partially hydrolyzed PVOH is between 75–95 mol-%, and that of fully hydrolyzed PVOH is above 95 mol-%. Properties affected by the degree of hydrolysis are surface activity, water solubility, and hydrophobicity of the polymer.

The hydrophobicity of PVOH increases with decreasing degree of hydrolysis. A lower degree of hydrolysis will give increased surface activity. On the other hand, the hydrophilicity of PVOH increases with increasing degree of hydrolysis. However, the water solubility of fully hydrolyzed PVOH is lower than that of partially hydrolyzed PVOH. This is linked to the crystallinity of the polymer, which increases with in-

Product	Viscosity in a 4% Solution, mPas	Degree of Hydrolysis, mol-%
KP 5-74	4.2–5.0	72.5–74.5
KP 5-82	4.5–5.2	80.0–83.0
KP 6-88	5.0–6.0	86.7–88.7
KP 6-98	5.0–7.0	98.0–98.8
KP 26-88	24.5–27.5	86.7–88.7
KP 47-88	45.0–49.0	86.7–88.7
KP 28-99	26.0 – 30.0	99.0 – 99.8

I. Viscosities and degree of hydrolysis of tested polyvinyl alcohol (PVOH) products.

creasing degree of hydrolysis. Fully hydrolyzed PVOH has to be heated when dissolving in water in order to break up the crystalline structure.

MATERIALS

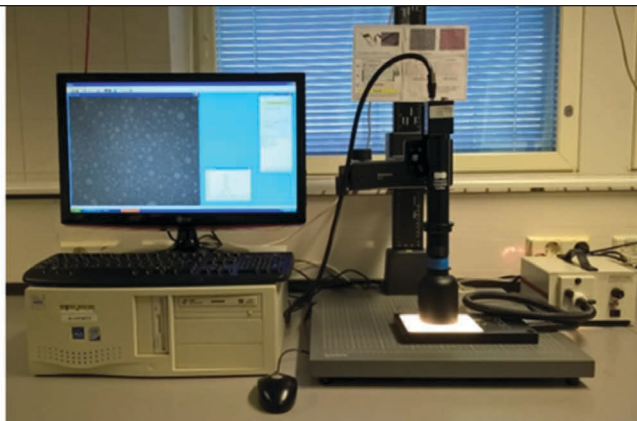
Bleached pre-refined softwood (SW) kraft pulp (pine) was used in laboratory scale studies (SR=19.7). In this work, PVOH with different viscosity (molar mass) and degree of hydrolysis was tested. In total, seven different polyvinyl alcohols from Kuraray (Tokyo, Japan) were investigated. The products are listed in **Table I**. All PVOH products were dissolved in hot water and then added as solutions.

The first number in the product name (trademarked KURARAY POVAL) represents the viscosity of a 4% solution in water. This is an indirect measurement of the molar mass (M). The higher the viscosity of a 4% solution is, the higher the molar mass. The second number in the name is the degree of hydrolysis given as mol-%. For example, KURARAY POVAL 28-99 (rep-

	Paper Trial	Board Trial
Furnish	A mixture of refined HW and SW from UPM Kymi mill (Kouvola, Finland).	The base stock consisted of 85% CTMP and 15% SW kraft pulp. CTMP was bleached spruce purchased from Rottneros AB.
°SR value of furnish	20.6	18.5
Dry strength additive	Cationic potato starch (Raisamyl 52001). Dosage 5 kg/metric ton of dry fibers in all trial points.	Cationic potato starch (Raisamyl 52001). Dosage 5 kg/metric ton of dry fibers in all trial points.
PVOH fibers	VPB105-2/4, dosage 15 %, in selected trial points.	VPB105-2/4, dosage 9 %, in selected trial points.
Retention system	C-PAM (Fennopol K3400, Kemira) and anionic polyacrylamide (Fennosil EO777, Kemira). Dosages of C-PAM and A-PAM were 100 g/metric ton and 100 g/metric ton, respectively, in all trial points.	C-PAM (Fennopol K3400, Kemira) and A-PAM (Fennosil EO777, Kemira). Dosages of C-PAM and A-PAM were 100 g/metric ton and 100 g/metric ton, respectively, in all trial points.
Foaming aids	SDS, PVOH KP 6-88, or PVOH KP 28-99.	SDS or PVOH KP 6-88

HW = hardwood; SW = softwood; CTMP = chemithermomechanical pulp; °SR = Schopper Riegler freeness; C-PAM = cationic polyacrylamide; A-PAM = anionic polyacrylamide; SDS = sodium dodecyl sulfate; PVOH KP 6-88 = PVOH with hydrolysis level of 88 mol-%; PVOH KP 28-99 = PVOH with hydrolysis level of 99 mol-%.

II. Furnishes and chemicals used in pilot scale trials.



2. (a) The foam was produced in a mixer, and foaming dynamics were recorded with a charge-coupled device (CCD) camera. (b) Determination of bubble size distribution of the fiber-foam mixture.

resented as KP 28-99 in this paper) has a viscosity of 28 mPas in a 4% solution and a degree of hydrolysis of 99 mol-%.

Based on laboratory scale studies, the most promising polyvinyl alcohols were tested in pilot scale trials. The anionic foaming aid studied in the pilot-scale trials was sodium dodecyl sulfate (Merck Chemicals Ltd.; Gillingham, UK). SDS ($\text{CH}_3(\text{CH}_2)_{11}\text{SO}_4\text{Na}$) is also mentioned in the recommendation of German BfR in the list of materials intended to come into contact with food. Furnishes and chemicals used in pilot-scale trials are listed in **Table II**.

Two types of trademarked KURALON PVOH fibers are available—a water-soluble and a non-water-soluble fiber. In this study, we used the water-soluble PVOH binder fiber. The water-soluble binder fiber is an adhesive in the form of a fiber, which is dissolved to form a film to glue the fibers together during the papermaking process. PVOH binder fibers need moisture, heat, and pressure to dissolve and act as a binder. The dissolving temperature of the PVOH fibers can be adjusted to fit the process parameters. In the pilot scale trials, one PVOH binder fiber (VPB 105-2/4) was tested. The thickness of VPB 105-2/4 was 1.17 dtex, cut length was 4 mm, and dissolving temperature was 60°C.

The furnish of the paper trial included a small amount of fillers (the fine paper base), but that was recirculated away at the beginning of trials. The softwood kraft pulp for board trial was taken from a mill process at 3.3% consistency. The chemithermomechanical pulp (CTMP) was delivered as dried bales. The CTMP was disintegrated with warm water (60°C) in the pulper. The SW was stored in a silo and the required amount was mixed with the CTMP. The fiber lengths of SW and CTMP were 2.23 mm and 1.77 mm, respectively. Fines content of SW and CTMP were 6.5% and 21.1%, respectively.

The cationic starch Raisamyl 52001 (Chemigate; Lapua, Finland) was dosed as a dry strength additive into the thick stock. The dosage of starch was 5 kg/metric ton of dry fibers in both trials. At this dose level, the zeta potential was at the desired level (from -10 mV to -15 mV). In the conventional water forming, zeta-potential of -10 to -15 mV has been thought to be the optimal range for papermaking [12,13].

METHODS

Studies in laboratory scale

The foaming properties of polyvinyl alcohols were studied by adding the pulp suspension (bleached pine kraft pulp) and PVOH solution in a transparent vessel ($\varnothing$ 120 mm). The fiber consistency was 0.6 % and the water temperature was 21°C. The vessel was then placed under the Netzsch drill pulp agitator (Netzsch Group; Selb, Germany), where it was clamped in (**Fig. 2a**). The mixing plate of the agitator was spun at 3800 rpm to generate the foam. The foam volume development over time was then monitored, and after mixing, it was stopped and the stability of the fiber-foam mixture was determined. In this study, foaming dynamics (generation and collapse) were recorded with a charge-coupled device (CCD) camera. Images were acquired at 5 s intervals. The volume of the fiber-foam mixture produced and the volume of drained liquid was monitored as a function of time. Foam stability was characterized by determining the time elapsed after cessation of mixing when the liquid volume reaches half of its initial height. The acquired image sequence (usually 100–300 images) was analyzed afterward using a semi-automatic method. The following quantitative measures of foamability and foam stability were calculated: $t(\Phi_{66\%})$, mixing time needed to reach 66% air content; Φ_{Max} , maximum air content during the mixing period; and $t_{1/2}$, a half-life time of foam.

The bubble size distribution (BSD) of the fiber-foam mixture was determined by collecting foam samples by dipping the cuvette (a Hele-Shaw cell with internal diameter of 1.6 mm) into the foam. The cuvette was placed on a backlight panel, and images of the cuvette were taken with a camera (**Fig. 2b**). BSD curves were obtained by analysis of a large number of bubbles (400–800 bubbles) by an image analysis method [14]. The Sauter mean radius $r_{[3,2]}$ was used for characterizing the BSD of foam.

Foam formed laboratory handsheets were made using a mold, as shown in **Fig. 3**. The size of the handsheet was 32 cm x 22 cm. The target grammage of the sheets was 120 g/m². Bleached pine kraft pulp was used as a raw material. When making a handsheet, the fiber-foam mixture was



3. The foam forming handsheet mold with one-sided dewatering.

poured into the top of the mold, where a funnel directed it to one side. Then, the fiber-foam mixture spread from one end of the mold to the other. This flow was enough to orient fibers in the flow direction. Finally, the fiber-foam mixture lay on top of the forming fabric that mimics a real paper machine. The funnel was then removed, and a plastic cover was placed on top of the foam to create a seal for the vacuum. The foam was removed by vacuum (-20 kPa). Following this process, the sheet was removed from the mold and was couched by placing an 8.2 kg weight on top of the sheet and two blotter papers. Couching time was 30 s.

Samples were wet pressed using an L&W wet press (Lorentzen & Wettre; Kista, Sweden) to consolidate wet sheets. Wet pressing was carried out in two steps. The first pressing was at 3.5 bar (5 min $\pm$ 2 s), and then the blotters were removed and replaced before the second wet pressing at 3.5 bar (2 min $\pm$ 2 s). Samples were dried by feeding sheets through a cylinder drying device (Kodak rotary drum dryer). The sheets were fed into the machine between two blotter papers

and were dried as they traveled around the cylinder. Each sheet went through the Kodak twice.

Studies in pilot scale

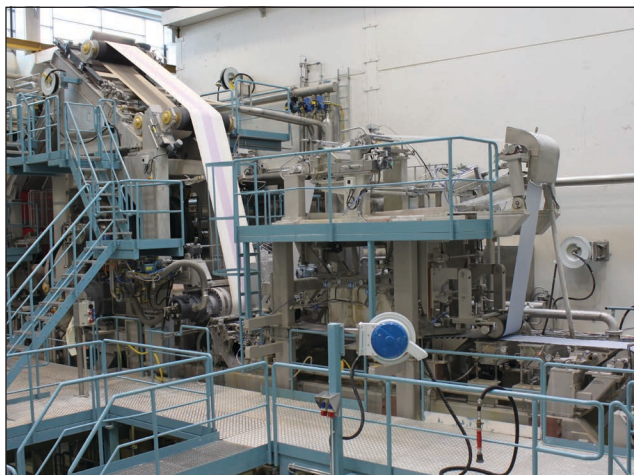
Based on laboratory scale studies, the most promising PVOH was verified in pilot scale. Water reference samples were also produced as a reference for foam formed samples. The pilot machine (**Fig. 4a**) consists of an approach system with different kinds of containers, a forming section, and a press section. The pilot machine was run in the hybrid mode both in paper and board trials. The foam was generated in a tank by mixing (**Fig. 4b**). The three-row headbox was in use. The press section consisted of a 1-nip shoe press having a 350 mm extended nip. Target grammages, machine speeds, and nip pressures are presented in **Table III**. After the wet pressing, the web was reeled and sheet samples were collected and dried for the laboratory analysis.

The main variables in the pilot trials were: i) type of foaming agent, ii) line load during wet pressing, and iii) use of PVOH fibers.

Cationic starch was dosed into the thick stock and it was allowed to adsorb onto the fibers for 15 min before feeding the stock into the short circulation. The retention chemicals were fed to the headbox flow. Cationic polyacrylamide (C-PAM) was fed using Retamix2 (after headbox pump) and anionic polyacrylamide (A-PAM) using Retamix1. The addition places of additives and foaming aids are presented on schematic layout picture (**Fig. 5**). PVOH fiber (VPB105-2/4) was added to the front chest. Three different foaming agents were used in the paper pilot trials: sodium dodecyl sulfate (SDS), PVOH having a hydrolysis level 88 mol-% (KP 6-88), and PVOH having a hydrolysis level 99 mol-% (KP 28-99). In the board trial, the foam was generated with either PVOH (KP 6-88) or SDS, which was added to the front chest.

Analysis of sheet properties

The sheet properties were analyzed according to the SCAN standards. The grammage was measured according to the



4. (a) Foam forming pilot machine at VTT. (b) Foam was generated in a tank.

	Paper Trial	Board Trial
Target grammage, g/m ²	80	120
Machine speed, m/min	500	400
Nip pressures, kN/m	400, 700, and 1000	400, 700, and 1000
Fiber consistency in headbox, %	Foam: 0.9 Water: 0.5	Foam: 1.3 Water: 0.7
Jet-to-wire ratio	Foam: 1.02 Water: 0.99	Foam: 1.02 Water: 0.99
Volumetric flow rate, l/s	Foam: 38 Water: 41	Foam: 34 Water: 38

III. Parameters of the pilot trials.

SCAN-P 6:75 Standard “Paper and board—Determination of grammage.” The thickness was determined with a Lorentzen & Wettre micrometer using SCAN-P 7:75 “Paper and board—Determination of thickness and apparent bulk density or apparent sheet density.” The combination of the sheet grammage and sheet thickness gives a measure of sheet density and bulk. Samples for the determination of dry matter content were taken before and after wet pressing. Samples were measured according to the standard method ISO 638 “Paper, board and pulps—Determination of dry matter content—Oven drying method.” The tensile strength and the strain at break were determined according to SCAN-P 38:80 “Paper and board—Determination of tensile properties. Part 2. Constant rate of elongation method,” and the elasticity of modulus was determined according to SCAN-P 67:93 “Pulps, papers and boards—Tensile strength, strain at break, tensile energy absorption, and tensile stiffness—Constant rate of elongation method (1,7 mm/s)” with the Lloyd measurement device. Internal strength

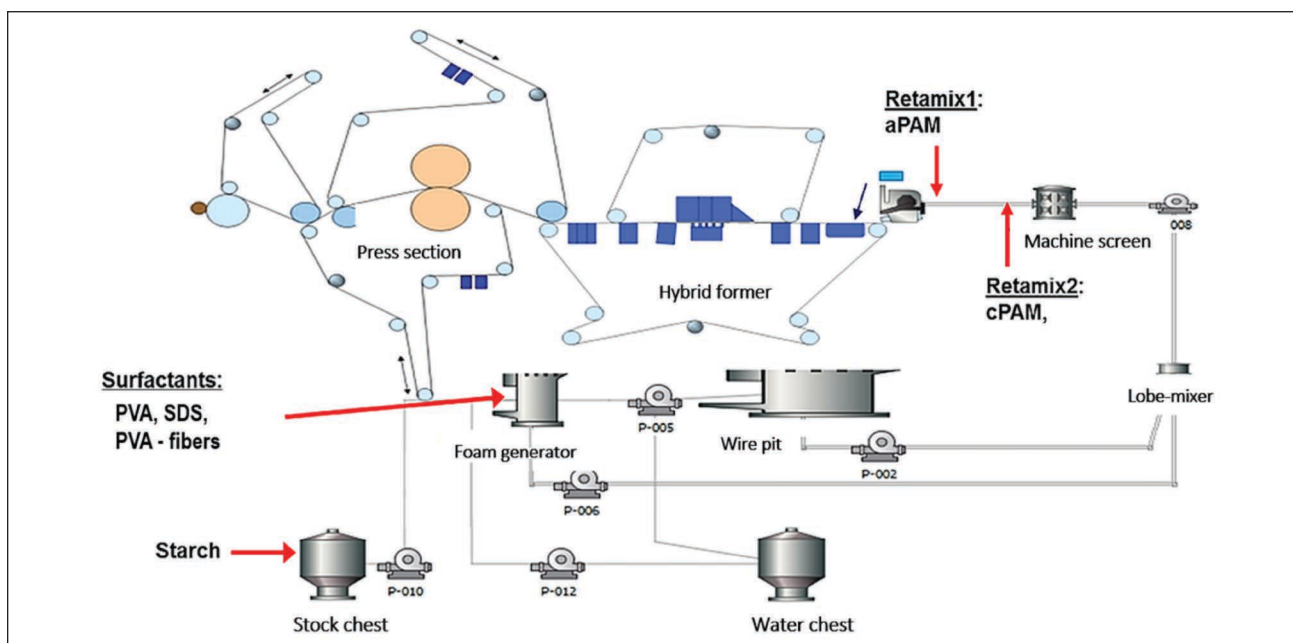
was determined using Scott bond according to TAPPI Standard Test Method T 569-09 “Internal bond strength (Scott type).” Z-directional tensile strength (internal bond strength) was measured according to a modified TAPPI T 541 om-99 “Internal bond strength of paperboard (z-direction tensile).”

RESULTS AND DISCUSSION

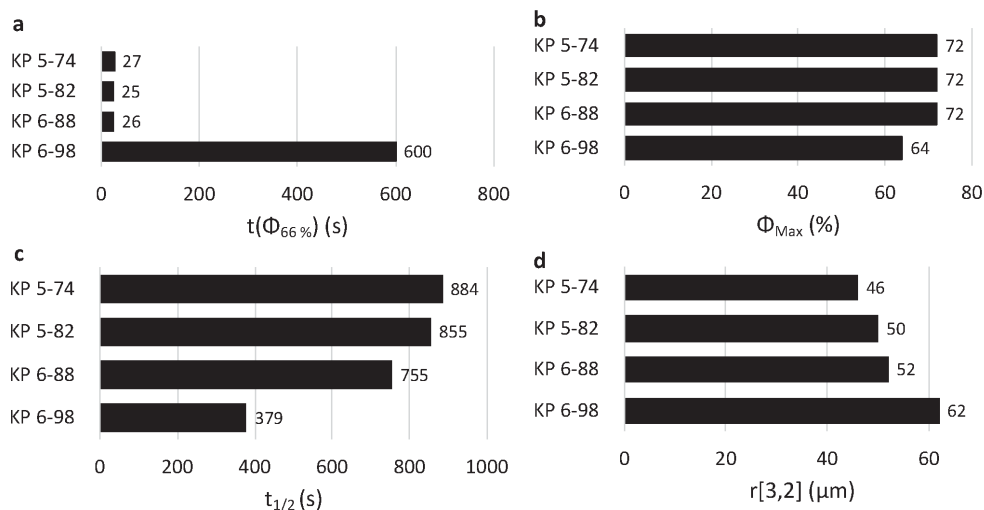
Laboratory investigations

Effect of degree of hydrolysis on foam properties

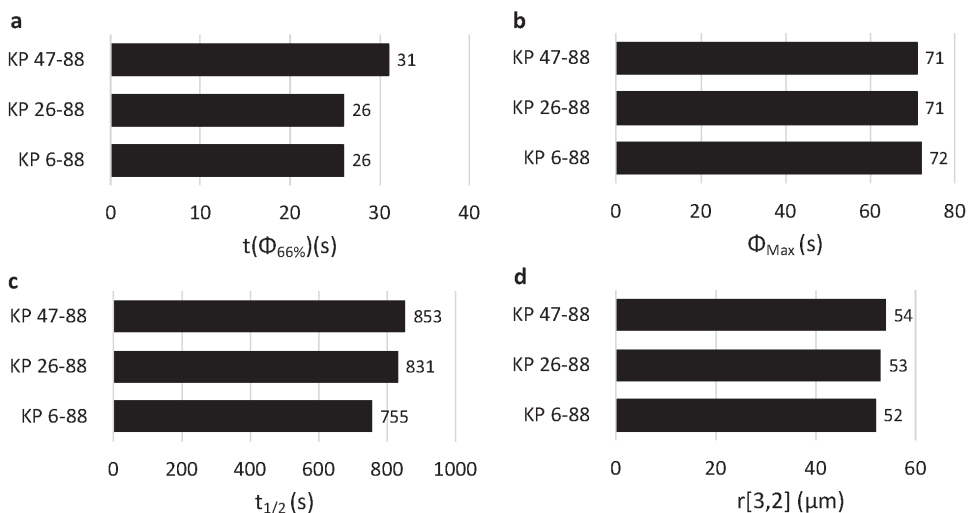
When we look at the effect of the degree of hydrolysis of PVOH on foam characteristics at a fixed molar mass (viscosity of 5–6 mPas) and dosage of 4 g/l, we can see that the degree of hydrolysis correlates with the stability of the generated fiber-foam mixture and the bubble size. **Figure 6** shows that a lower degree of hydrolysis gives a more stable foam and a smaller bubble size. The bubble size decreases from 62 µm to 46 µm and foam halftime increases from 379 s to 884 s with decreasing degree of hydrolysis (degree of hydrolysis from 98



5. Process layout and dosage places in the additives process.



6. Effect of degree of hydrolysis on foam properties (dosage of PVOH was 4 g/l): (a) foamability characterized using $t(\Phi_{66\%})$; (b) maximum air content; (c) stability of foam characterized using half-life time $t_{1/2}$ (s); and (d) size of the bubble characterized using Sauter mean radius $r[3,2]$ (μm).



7. Effect of molar mass (viscosity) on the stability of generated fiber-foam mixture (dosage of PVOH was 4 g/l): (a) Foamability characterized using $t(\Phi_{66\%})$; (b) maximum air content; (c) stability of foam characterized using half-life time $t_{1/2}$ (s); and (d) size of the bubble ($r[3,2]$ (μm)).

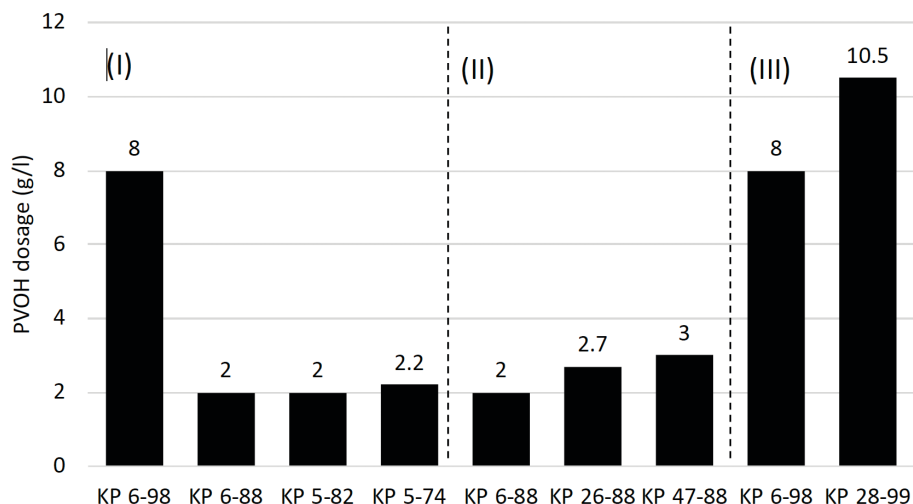
mol-% to 74 mol-%).

The biggest difference in foamability was between the partially hydrolyzed PVOH (KP 6-88) and fully hydrolyzed PVOH (KP 6-98). Air content of 66% was reached for the partially hydrolyzed products in about 26 s, whereas for the fully hydrolyzed KP 6-98, the 66% air content was not reached during the 600 s test. The max air content, Φ_{MAX} , for the partially hydrolyzed PVOH was 72%, and for the fully hydrolyzed PVOH, it was only 64%. This finding is consistent with that of Hou and Wang [15], who also presented that partially hydrolyzed PVOH is more effective in foaming than fully hydrolyzed PVOH. Foamabilities of KP 5-74 and KP 5-82 were very similar

to that of KP 6-88. For all three products, $t(\Phi_{66\%}) \sim 26$ s and $\Phi_{MAX} \sim 72\%$ were reached. In other words, there was no difference in foamability between products having a degree of hydrolysis between 74 mol-% and 88 mol-%. However, the stability of generated fiber-foam mixture was almost 20% better when using the 74 mol-% product instead of the 88 mol-% product (Fig. 6).

Effect of molar mass on foam properties

Three polyvinyl alcohols were compared with the same degree of hydrolysis (88 mol-%) but with different molar mass (different viscosity). The dosage of foaming aid was 4 g/l in



8. The effect of PVOH type on minimum dosage needed to obtain an air content of $\Phi > 70\%$: (I) effect of degree of hydrolysis on dosage; (II) effect of molar mass (partially hydrolyzed products) on dosage; and (III) effect of molar mass (fully hydrolyzed products).

each trial point. There were no big differences in foamability seen. The time to reach 66% air content was the longest (31 s) for the highest molar mass product (KP 47-88). For KP 6-88 and KP 26-88, it took slightly shorter time (26 s) to reach the 66% air content. Furthermore, the maximum air content of all three polyvinyl alcohols was 71%–72%. KP 6-88 gave the highest air content (72%).

Figure 7 shows that the foam stability increased with molar mass. When the viscosity of PVOH increased from 6 mPas up to 47 mPas, the foam half time increased from 755 s to 853 s (about 13%). There were no significant differences in bubble size between the PVOH products (for all foams $r[3,2] \sim 53 \mu\text{m}$).

Effect of PVOH type on minimum dosage needed to obtain air content above 70%

The previous tests were done with a fixed dosage of PVOH (4 g/l). Next, we looked at the minimum PVOH dosage needed to obtain an air content Φ above 70%. **Figure 8** shows that the difference in dosage level required is large, especially between the fully hydrolyzed PVOH (KP 6-98) and partially hydrolyzed PVOH (such as 6-88). For fully hydrolyzed polyvinyl alcohol with 98-mol% degree of hydrolysis, we needed to dose 8 g/l of PVOH compared to the partially hydrolyzed grade where the dosage level required to reach 70% air content was only 2 g/l. When making foams, the foaming agent must rapidly diffuse to the newly created water-air interface. The diffusion is influenced by the molar mass of the foaming agent. The fiber suspension could be foamed, even though the molar mass of polymeric PVOH was much higher than that of the small molar mass foaming agent (e.g., molar mass of KP 6-88 is about 37 kg/mol and molar mass of SDS is about 0.288 kg/mol). Looking at Fig. 8, it is apparent that with increasing molar mass, the required dosage level of PVOH increases. A

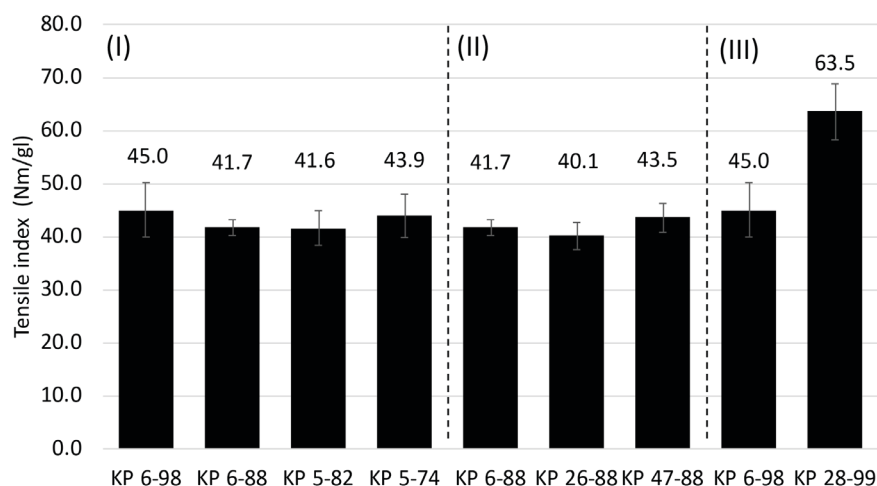
larger dose is required to keep the number of molecules the same as the molar mass of PVOH increases.

For KP 6-88, the minimum dosage was 2 g/l and for KP 47-88 the minimum dosage was 3 g/l. One should note that this is a 50% increase in dosage. For the fully hydrolyzed products (KP 6-98 and KP 28-99), we see the same trend; that is, with increasing molar mass the required dosage level increases. For the fully hydrolyzed products, the required dosage levels were much higher (8 and 10.5 g/l).

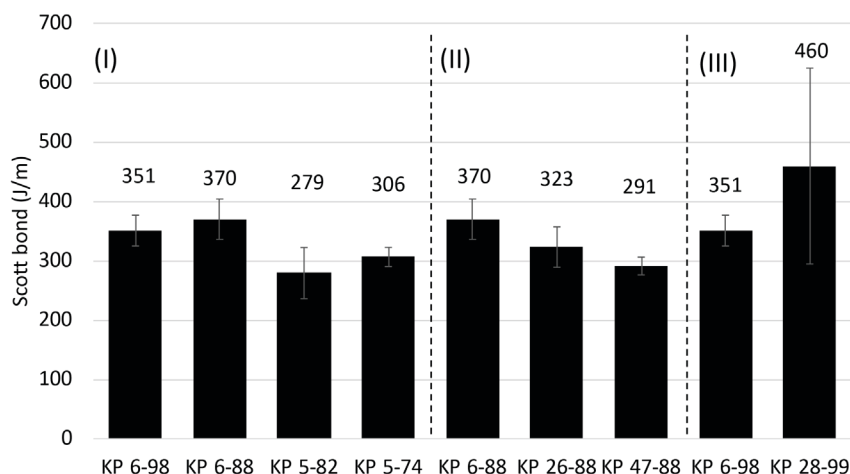
It is important to point out that the dosage levels presented in Fig. 8 are optimal when making handsheets in the laboratory. This kind of static mold is sensitive to rheological properties of the foam-fiber mixture, and therefore, a long-living foam with an air content of 65%–70% is needed. If the foam air content drops below 55%, the pseudoplastic behavior of the foam disappears [16]. In pilot scale, the foam-fiber mixture is transferred quickly from the headbox to the forming section where the foam-fiber mixture collapses under the influence of the suction boxes. As a consequence, the stability of foam needed in pilot scale does not have to be as good as when using a handsheet mold.

The effect of PVOH type on strength properties of handsheets

Handsheets were made with PVOH dosages presented in Fig. 8. Tensile index and Scott Bond of samples were determined (**Fig. 9** and **Fig. 10**). The handsheet mold orients the fibers to some extent; thus, the tensile index was larger in machine direction than in the cross direction. Therefore, geometric mean values are presented. When looking at Fig. 9, we do not see a correlation between the tensile index and degree of hydrolysis of PVOH or between tensile index and molar mass (viscosity) of PVOH. The only product that stands out is KP 28-99, which gives a higher tensile index than the other products. The dosage level was also the highest for KP 28-99,



9. Tensile indexes (geometric mean values) of foam-formed handsheets. The error bars represent the geometric standard deviation (n=10).



10. Scott bond of foam-formed handsheets. The error bars represent the standard deviation (n=10).

but not that different from KP 6-98, which only shows similar values for the tensile index as KP 6-88.

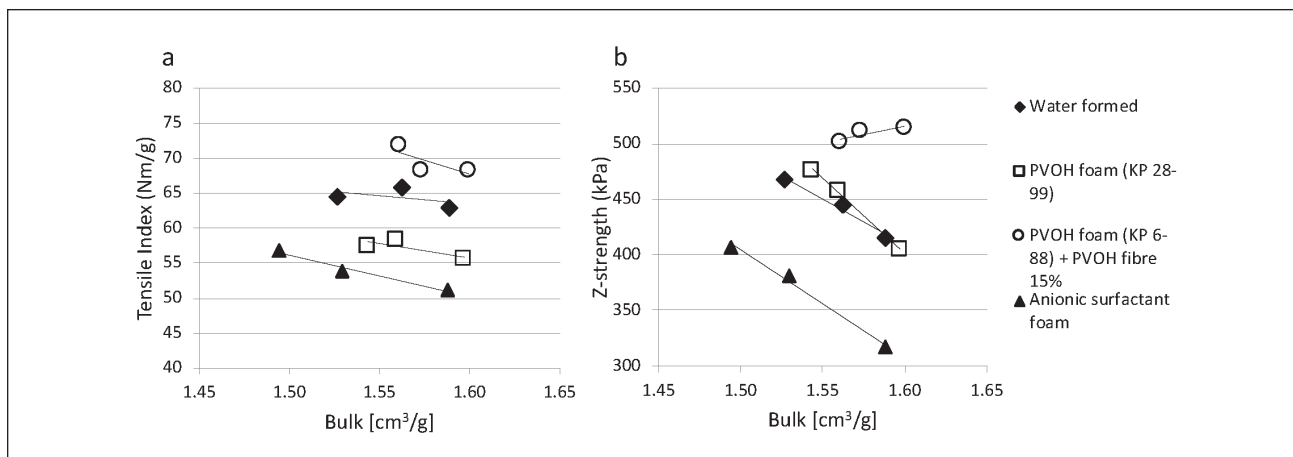
For Scott bond (out-of-plane strength), we can see in Fig. 10 a negative correlation with molar mass for the partially hydrolyzed products, which was unexpected. KP 6-88 gave the highest Scott bond of the partially hydrolyzed products. For the fully hydrolyzed products, Scott bond increased with the molar mass of the PVOH. KP 28-99 gave the highest Scott bond value.

Results from the paper pilot trial

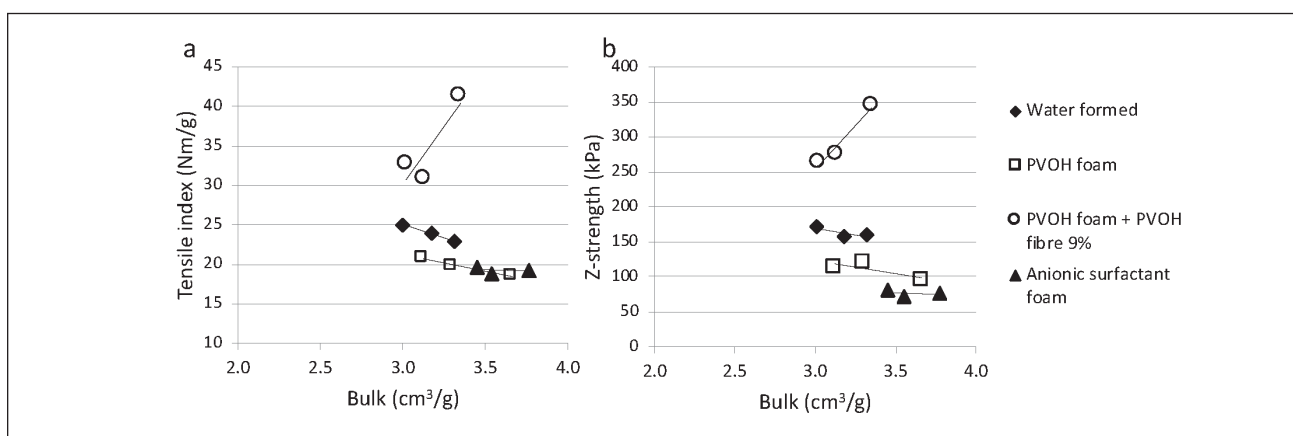
The main findings from the paper pilot trials were that PVOH worked well as a foaming agent. We achieved the target air content ($\Phi > 40\%$) and bubble size when PVOH was used as the foaming agent. As explained earlier, the stability of foam

needed in pilot scale does not have to be as good as when using a handsheet mold. **Figure 11** shows that the strength properties of samples were better when using PVOH as a foaming agent instead of the anionic foaming agent (SDS). PVOH is a hydrophilic polymer carrying hydroxyl groups on repeating units. This permits the development of hydrogen bonds with hydroxyl and carboxyl groups of cellulose fibers, thus enhancing strength properties of paper [17]. However, the strength of foam-formed paper using KP 28-99 as a foaming agent was lower than that of the water formed sample. The tensile index of foam-formed samples (KP 6-88) with PVOH binder fibers was, however, better than that of the water reference sample.

The highest z-directional strength was achieved by using



11. Strength properties of paper samples vs. bulk: (a) tensile index as a function of bulk, and (b) z-directional strength as a function of bulk.



12. Strength properties of board samples vs. bulk: (a) tensile index as a function of bulk, and (b) z-directional strength as a function of bulk.

PVOH binder fibers and generating the foam using KP 6-88. The z-directional strength of water formed samples and samples made using KP 28-99 as the foaming agent were at the same level.

The anionic surfactant gave the lowest strength. A probable explanation as to why PVOH as a foaming agent gives better strength properties than the anionic surfactant is that PVOH, being nonionic, does not interfere with other chemicals (such as cationic starch) as opposed to the anionic foaming agent. The dosage of cationic starch was 5 kg/metric ton of dry fibers in every trial point. The higher tensile index and z-strength for sample points with PVOH foam and PVOH fibers is due in particular to the PVOH binder fibers. The PVOH fibers are partially dissolved during the papermaking process, making it an adhesive that binds the cellulose fibers to each other.

Results from the board pilot trial

The results of board trials were in line with the results from the paper trials. The dosage of cationic starch was 5 kg/metric ton of dry fibers in this trial also. **Figure 12** shows that the

highest strength was reached with PVOH binder fibers. For tensile index, the anionic foaming agent and PVOH were on the same level, whereas the use of PVOH foam and PVOH binder fiber gave the highest tensile index. For z-directional strength, the anionic surfactant gave the lowest strength and the PVOH foam with PVOH fiber gave the highest strength. An interesting observation with the PVOH fiber points is that strength increases with increasing bulk, which is an opposite trend compared to other samples.

CONCLUSIONS

The aim of this study was to investigate the use of polyvinyl alcohol as a foaming agent for foam formed paper and board, as well as which PVOH parameters influence the foamability of PVOH. Furthermore, we studied whether PVOH could also be used as a strength aid in foam formed paper.

The results from the laboratory investigations showed that the degree of hydrolysis of PVOH had a strong effect on the foamability of PVOH. A lower degree of hydrolysis gave a more stable foam and a smaller bubble size. Foamability decreased significantly when the degree of hydrolysis increased from 88

to 98 mol-%. The effect of molar mass on foamability was less pronounced. We saw an increase in foam stability and bubble size with increasing molar mass, but we did not see any effect on maximum air content. PVOH dosage levels need to reach >70% air content (Φ) varied from 2 g/l up to 10.5 g/l. The lowest addition levels of PVOH required were achieved with a low molar mass PVOH with a low degree of hydrolysis.

The best strength properties (without binder fibers) were achieved when using fully hydrolyzed PVOH as the foaming agent. Strength properties (both in- and out-of-plane) of samples made using PVOH were better than those made using an anionic foaming agent (sodium dodecyl sulfate, SDS). By adding PVOH binder fibers to the pulp, we were able to further enhance the strength properties of paper and board.

The results from the paper and board pilot trials confirmed that PVOH worked well as a foaming agent. The strength properties were better when using PVOH as a foaming agent compared to an anionic foaming agent, but the strength properties were lower than that of water formed paper and board. **TJ**

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ABOUT THE AUTHORS

I (Gottberg) work for a PVOH producer, and we participated in a foam formed paper project at VTT in Finland. Foam forming technology has a huge potential for paper, and this work supports VTT's previous work on foam formed paper and foaming agents.

We discovered that partially hydrolyzed, low molecular weight PVOH can work as a foaming agent. One surprising finding was that one of the tested PVOH products imparted higher strength properties compared with the other products tested, and a next step would be to understand why the KP 28-99 product imparted these higher strength properties. This work can ultimately help mills choose the correct PVOH to use as a foaming agent.



Gottberg



Salminen



Lappalainen

Gottberg is regional marketing manager, Kuraray Europe Nordic AB Oy, in Vantaa, Finland. Salminen is research team leader and Lappalainen is senior scientist at VTT Technical Research Centre of Finland, Jyväskylä, Finland. Email Gottberg at jens-mikael.gottberg@kuraray.com.

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