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MULTILAYERING OF FINE PAPER WITH 3-LAYER HEADBOX AND ROLL AND BLADE GAP FORMER

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Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Department of Forest Products Technology, for public examination and debate in Council Room at Helsinki University of Technology (Espoo, Finland) on the 14th of May 2004 at 12 noon.

Helsinki University of Technology
Department of Forest Products Technology
Laboratory of Paper Technology

Teknillinen korkeakoulu
Puunjalostustekniikan osasto
Paperitekniikan laboratorio

PREFACE

This dissertation is based on research carried out at Metso Paper between 1998 and 2003. Experimental studies were conducted at the Metso Paper Technology Center and VTT Processes in Jyväskylä. All work was completed under the guidance of Metso Academy and funded by Metso Paper. The main goal of the research was to elucidate the behavior of fibers and fillers in the paper thickness direction when layering with a 3-layer headbox and a roll and blade gap former.

I would like to express my thanks to Professor Hannu Paulapuro of the Laboratory of Paper Technology at HUT for his guidance of my work.

For my supervisors at Metso Paper, Pekka Pakarinen and Dr. Johan Grön (also one of my cowriters), I owe a debt of gratitude for their inspiration, comments, and critique.

Thanks are also due my former bosses, Lauri Verkasalo (M-Real) and Hannu Korhonen (Metso Paper), who made it possible for me to carry out my research work and encouraged me to forge on.

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Finally, I would like to express my deepest gratitude to my wife Eija and my son Tuomas for their patience and support of my work.

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ABSTRACT

The aim of this study was on the layering of fine paper with a 3-layer headbox and roll blade gap former. It consisted of methodological development and laboratory scale studies, as well as layering studies on the pilot paper machine scale. The potential of layered structures in papermaking and the phenomena affecting layer mixing were also studied.

Filler distributions were characterized by two parameters - filler distribution shape and symmetry factors. The method developed made it possible to apply a statistical approach to experiments when studying the impact of typical wet end control parameters on the control of filler distributions and the contribution of filler distributions to paper quality parameters. A method by which the center layer fiber distribution may be characterized from the final paper is also presented. The method is based on the use of dyed fibers and a spectrofotometer.

In addition, a laboratory device, a multilayer handsheet former for making layered structures, is presented. The process closely resembles a real continuous multilayer process by providing water phase interactions between layers during forming and two-sided dewatering characteristics. In a case study, retention chemical and filler layering with WFC base paper was performed by the multilayer handsheet former. Surface roughness decreased and brightness increased when the filler content in paper surfaces was increased. At constant filler content, paper strength increased as the filler concentration in the paper surfaces increased.

The distinction between roll dewatering and blade dewatering in terms of layer mixing as well as differences in the mixing behavior of fibers and fillers in different dewatering phases was studied. Major fiber mixing takes place during the free jet and roll dewatering phase. In blade dewatering, fiber movements are related to formation improvements. The greatest mobility differences between fibers and fillers were found in the blade dewatering phase in roll and blade dewatering. Filler distributions were significantly affected during blade dewatering, with the mobility of the fibers remaining insignificant.

The relationship between typical fine paper quality parameters and filler distributions was studied. Formation improvement and densification of the paper were achievable at the same running conditions. Low porosity was achieved by evenly distributed constituents (good formation) and a local rich filler concentration somewhere in the paper structure in the paper thickness direction. Oil absorption two-sidedness was minimized by symmetrical filler distributions. The combination of all these quality factors required the filler distribution to be symmetrical and as u- or turned u-shaped as possible.

The use of additives layering as a part of paper quality control was also studied. Multilayering was found to be an effective tool for the control of filler distributions. On the other hand it was shown that, in order to get optimized impact of the multilayering on quality properties, the other process variables also need to be controlled.

Keywords: layering, fine paper, 3-layer headbox, multilayer handsheet former, filler distribution, fiber mobility, additives layering, layer mixing
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II Puurtinen, A., Saari, T., Grön, J., A laboratory study on the chemical layering of WFC base paper. 15th PTS CHT Symposium: Chemische Technologie der Papierherstellung, München, Germany, 37/1…37/11 (2002).

Puurtinen, A., Saari, T., Grön, J., A laboratory study on the chemical layering of WFC base paper. Professional Papermaking, published by Wochenblatt für Papierfabrikation, 1(1): 22-25 (2003).

III Puurtinen, A., Wet end control of filler distributions using additive layering principles. Paper Technology, 44(4): 33-40 (2003).

IV Puurtinen, A., Controlling filler distribution for improved fine paper properties. Accepted (13.6.2003) for publication in Appita Journal.

V Puurtinen, A., Oksanen, A., Control of fiber mobility and filler distribution in wet end layering. NPPRJ, 18(2): 217-225 (2003).

LIST OF SYMBOLS AND ABBREVIATIONS

The following symbols and abbreviations are used in this summary:

Fsym	Symmetry factor
Fu	Shape factor
Fts	Top side filler content
Fbs	Bottom side filler content
Fcl	Center filler content
$Fsym_e$	Estimate for the symmetry factor
Fu_e	Estimate for the shape factor
Fts_e	Estimate for the top side filler content
Fbs_e	Estimate for the bottom side filler content
Fcl_e	Estimate for the center filler content
Psym	Retention chemical dosing symmetry factor
Pu	Retention chemical dosing shape factor
Vane length	Layering vane length
Q	Headbox flow rate
FRvac	Forming roll vacuum
LBvac12	Combined vacuum of the suction boxes 1 and 2 in the LB-loading unit
BW	Basis weight
CIE	CIE-color coordinate system
L*	Lightness
b*	Yellow / blue axis
CTMP	Chemi thermomechanical pulp
SC	SC paper
WFC	Woodfree coated paper
MFP	Metered film press
MSP	Metered size press
HSWO	Heat set web offset
CS	Coherent structure
MD	Machine direction
CD	Cross direction
I_{MH}	Mixing intensity at a specific location in the free jet
N	Crowding factor
FFT	Fast fourier transform
RMS	Root mean square
TS	Top side
BS	Bottom side
$Poro_e$	Estimate for the porosity
$Forma_e$	Estimate for the formation index
$Oilab_e$	Estimate for the oil absorption two-sidedness

INTRODUCTION

The multilayering of paper has been commonly practiced in the manufacture of paperboard and tissue grades and it has also been attempted with printing and writing paper grades. In conventional paper manufacturing, the raw materials are mixed. However, the objective of multilayering is to produce better paper from the same raw materials, or the same grade of paper from lower quality raw materials. It is thus motivated by the need to control factors affecting the cost and quality of the paper.

Layered paper structures can be created in many ways. Separately formed sheets can be bonded at suitable stages of the process and additional layers can be formed on top of an existing sheet of paper. These methods are common in the manufacture of paperboard where the goal is to produce layers with distinct fiber structures. The coating of paper can also be loosely interpreted as a multilayering process. Multilayering can also be accomplished using a so-called multilayer headbox where layers are joined after passing through layering vanes either inside or outside the headbox. The main motivation for using a multilayer headbox is the simplicity and cost-effectiveness of the process compared to the equipment and systems needed for separate sheet formation.

A number of experiments have been conducted to study and observe the potential of multilayering in creating layered paper samples. Less attention has been paid to the extent to which the layers tend to mix together during the continuous paper manufacturing process.

One of the main goals of this work was to clarify the process parameters affecting layer mixing during roll and blade gap forming with a 3-layer headbox. Attention was paid to the impact of different dewatering phases on layer mixing and the mixing of various raw materials.

Gap forming produces layered paper structures by itself. The ZD filler distribution can be adjusted by changing the forming conditions. The impact of changes in the forming conditions on the filler distribution also depends on the paper stock used. In the manufacture of SC paper, for example, TMP-based stock produces a deep U-shaped filler distribution, whereas GW-based stock yields a smoother distribution.

This study examined the filler distribution of fine paper and factors affecting fiber migration in the paper sheet’s center layer. The results were examined from the perspective of control factors (machine parameters) and dewatering during formation. The goal was to find the most significant factors affecting center layer fiber migration and the formation of the filler distribution. A secondary goal was also to estimate what factors will produce selective fiber layering (layer purity) and the desired filler distribution simultaneously.

The study examined the dependence of some key fine paper quality factors on the filler distribution. The examination was based on empirical models created to depict the dependence of filler distributions and the quality variables examined on the control parameters.

Laboratory scale sheet molds are fairly widely used tools in the study of papermaking. This type of research includes raw material studies to determine the potential of stock components, or the partial or complete simulation of manufacturing processes. One of this study's goals was to introduce a laboratory sheet mold that could be used to partially simulate multilayer headbox layering and to investigate the paper technology potential of multilayering using purely layered paper samples. The multilayer sheet mold approach was also used to develop the methods used to determine the purity of the layers.

OBJECTIVES AND STRUCTURE OF THE STUDY

The main objective of this work was to study the process parameters affecting layer mixing during roll and blade gap forming with a 3-layer headbox and to review the significance of layered structures on fine paper properties. One objective was also to distinguish various wet end mechanisms affecting the filler distributions and fiber mobility in the paper thickness direction during the paper making process. The work was based on laboratory and pilot paper machine studies. The main emphasis was on the study of the role of the filler distributions.

The main objective was divided into the following sub-objectives:

1. To review the current knowledge of:
- the importance of layered structures
- various layering techniques
- process variables controlling filler distributions and fiber mobility
- the methods used to evaluate filler distributions and fiber mobility

2. To introduce and test a laboratory device for making layered paper structures.

3. To develop a method to characterize filler distribution, and to evaluate the role of different wet end processes in controlling it.

4. To evaluate the significance of filler distribution on some fine paper quality properties.

5. To develop methods to determine fiber mobility in the paper thickness direction and to evaluate the role of different process variables in controlling it.

6. To distinguish different process variables controlling filler distribution and fiber mobility in the paper thickness direction.

	Publication	
I	Multilayer Handsheet Former	1,2
II	A laboratory study on the chemical layering of WFC base paper	1,4
III	Wet end control of filler distributions using additives layering principles	1,3,6
IV	Controlling filler distribution for improved fine paper properties	1,3,4
V	Control of fiber mobility and filler distribution in wet end layering	1,5,6

MATERIALS AND METHODS

Multilayer handsheet former

Laboratory handsheet forming is a widely used method to produce paper sheets under controlled circumstances. The basic research into the potential of fibers and furnishes with respect to paper quality issues is often based upon laboratory handsheet studies. Some of these methods may also be helpful in producing layered sheet structures [1-9].

A common way to create a layered sheet is to filter new layers through already formed layers [10-14]. Another possibility is to produce layered sheet structures by bonding wet, single layered sheets together under pressurized conditions [15,16]. One task in the laboratory sheet forming field is to some extent to imitate the continuous forming processes [1,2,4]. Two common features of the above-mentioned laboratory formers are that basically they can be used to produce layered structures, but that the dewatering is single-sided. Only a few laboratory scale methods are capable of two-sided water removal [17-19].

A characteristic of the roll-blade gap forming process is two-sided dewatering and the consequent influence that has on paper structure and quality properties. The process enables a symmetrical paper structure which at least for most printing paper grades is a desired quality property. When simulating the paper structure produced by a modern gap forming process, it is necessary to create a symmetrical paper structure in order to study the role and interaction of different additives (chemicals, fillers) on paper quality properties.

In this study, a novel method of producing layered handsheets (*Fig. 1*) is presented [I]. The basic idea of the multilayer sheet former is to create a layered sheet structure between two fabrics. An advantage of this handsheet forming method is its symmetrical dewatering characteristics, which resemble the dewatering characteristics of the gap forming process.

Fig. 1. Multilayer handsheet former.

Fig. 2 shows the design principle of the equipment. The sheet former's chamber can be divided into two to three parts using removable divider plates. The fabric frames are mounted in a vertical position at both ends of the chamber. The movements of the fabrics are controlled by lateral pneumatic cylinders. The dividing plates in the chamber are removed during the sheet forming process by vertical cylinders to allow a two to three layered sheet to be formed between the fabrics.

Typical process variables:

- air mixing time 15 s and intensity 100 - 150 l/min,
- air exhausting time 12 s,
- forming speed from 15 * 10^{-3} m/s to 30 * 10^{-3} m/s (movements of fabrics)
- constriction force 250 N.

In order to make good quality stratified sheets, all these process variables have been optimized in line with fundamental research.

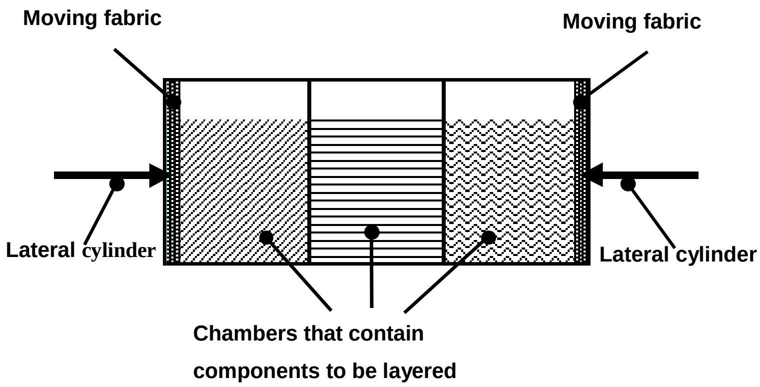


Fig. 2. Multilayer handsheet former.

Fig. 3 shows the operating principle of the multilayer sheet former. The pulp and chemicals (fillers, retention chemicals, wet end additives) are added manually into each of the chambers. After a stage of mixing with compressed air, the actual sheet forming begins by pushing the fabrics towards each other, which removes water from the surface layers (*Fig. 3*, step 1 -> step 2). When the fabrics are moved close to the dividing plates (step 2), the vertical cylinders remove the dividing plates (step 3). The middle layer will then be dewatered through the surface layers and thus create a multilayer sheet between the fabrics (step 4).

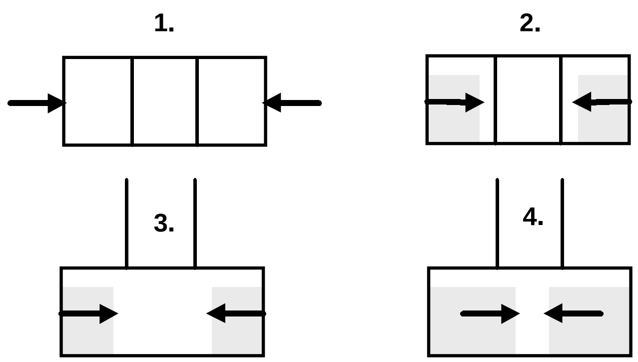


Fig. 3. Operating principle of the multilayer handsheet former.

A more detailed depiction of the multilayer handsheet former has been presented in Appendix 1.

Pilot paper machine

Test papers were made on the pilot paper machine located at the Metso Paper Technology Center at Rautpohja, Finland. The furnish entering the headbox was separated into three layers. The main stock feed line upstream of the headbox was divided into three equal-sized lines. Each line had its own feed pump and machine pressure screen. The headbox was a three-layer hydraulic headbox. The turbulence generator had six rows of tubes, which were split into three sets of equal-numbered (two/two/two) rows. The layers after the turbulence generator were separated by 2 mm thick flexible layering vanes. The last 50 mm length of the free end (downstream end) of the 2 mm layering vanes were tapered to a final thickness of 0.7 mm. (*Fig. 4*)

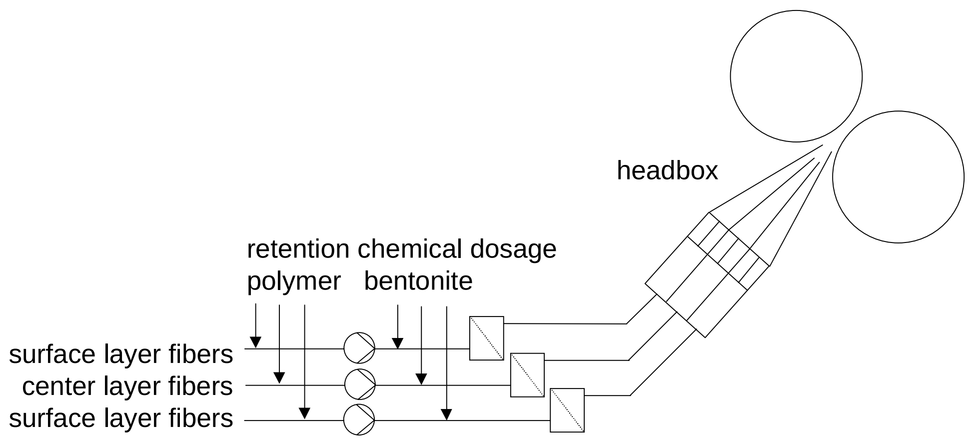


Fig. 4. The additives and fiber layering wet end arrangements.

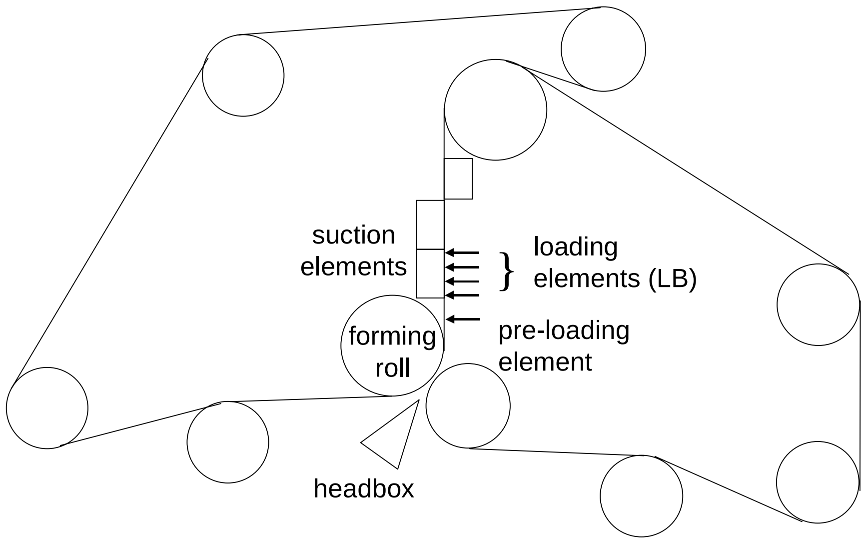


Fig. 5. The former.

The former was a roll-blade gap former equipped with loadable blades. The wrap angle, i.e. the area where the outermost fabric is producing gap pressure against the forming roll, was 15 degrees. The radial width of the forming roll suction zone was also 15 degrees. The unit following the forming roll is called an LB-loading unit. The loading side of the LB-loading unit consisted of one pre-loading element and four loading elements. The fixed side of the LB-loading unit (opposite the loading side) consisted of two suction box zones. The lower zone was located opposite the loading blades (*Fig. 5*).

The forming fabrics were two-layer fabrics designed for fine paper. The retention chemical dosage application took place after the division of the main stock line. The retention chemical was introduced into the stock before the feed pump. The bentonite was introduced after the feed pump and before the machine pressure screen. Retention chemicals used were bentonite Hydrocol O and Allied Colloid's cationic PAM Percol 47. The line introducing furnish to the center layer could be temporarily connected to a separate furnish source, which made it possible to use different furnishes in the center layer than in the surface layers (*Fig. 4*).

More detailed depiction of the test equipments has been presented in Appendix 2.

Analysing of filler distributions

The filler distribution in paper in the paper z-direction is determined by splitting the sheet into 10-15 layers by means of adhesive tape and then by analysing the filler content of each layer by an incineration method in accordance with the SCAN P5:63 standard. Paper splitting technique itself is laboratory handiwork and is based on defined laboratory work instructions.

The analysis method of filler distribution is assosiated various types of error sources. Errors can be basically devided into two main categories: errors related to the analysis technique including the splitting technique itself and further sample treatment such as sample weighting and ashing, and errors related to the paper's structural issues such as homogeneity of the paper structure and material properties.

In planar directions (MD and CD) the paper homogeneity is mainly related to the paper making process stability. In the paper z-direction the overall paper process stability but also paper z-directional internal structure is affecting the paper splittability in the paper z-direction. Studies related to the mechanisms and measurements of the layered orientation structure of paper sheet, Erkkilä [20] found that the splittability of the paper sheet was not dependent on the direction the splitting has been conducted.

Repeatability of the splitting technique and the accuracy of the whole filler content measurement chain has been evaluated by analysing the filler distributions from 5 individual points in a single A4 size sample and comparing the results (*Fig. 6*). The sample was a production machine made fine paper sample.

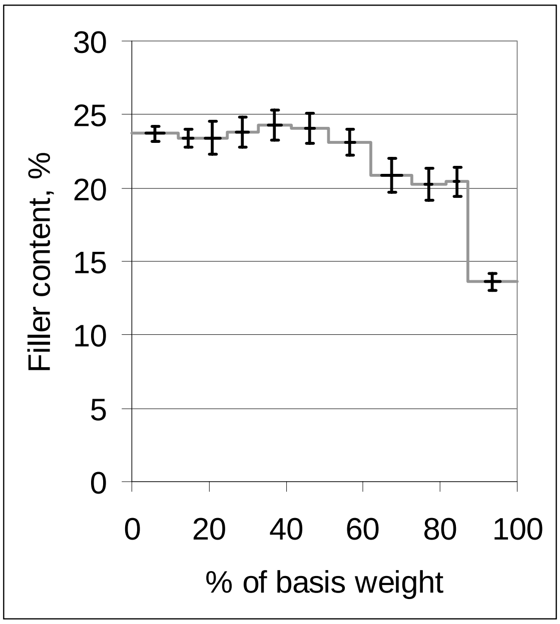


Fig. 6. An example of typical filler distribution.

The average standard deviation of the filler content measurements is 0.91 and it's standard deviation 0.23. The average standard deviation and it's standard deviation for the percentage basis weights are 1.56 and 0.62 . The result shows that the splitting as a technique in this particular fine paper case is relatively well repeatable and the accuracy of the filler content can be considered to be within +/- 1.2 % units.

Tape splitting method is widely used in the existing literature [20-31].

Characterization of filler distributions

To be able to apply a statistical approach to the analysis work, the filler distributions needed to be converted into a more appropriate form. In this study the characterization of the filler distribution was defined based upon two characteristics, the symmetry factor, *Fsym* and the shape factor, *Fu*. The mathematical definition of the filler symmetry factor is as follows:

$$Fsym = Fts/Fbs-1,\ \text{when}\ Fts/Fbs>=1, \qquad (1)$$

$$Fsym = -(Fbs/Fts-1),\ \text{when}\ Fts/Fbs<1, \qquad (2)$$

where *Fts* is the top side filler content and *Fbs* is the bottom side filler content. The shape factor of the filler content, *Fu* is defined,

$$Fu = (Fts+Fbs)/(2*Fcl)-1,\ \text{when}\ (Fts+Fbs)/(2*Fcl)>=1, \qquad (3)$$

$$Fu = -(2*Fcl/(Fts+Fbs)-1),\ \text{when}\ (Fts+Fbs)/(2*Fcl)<1, \qquad (4)$$

where *Fcl* is the center layer filler content.

For the calculation of the *Fsym* and *Fu*, the representative top, center and bottom side filler contents from the original measured filler distributions are needed. For the determination of representative values, filler distribution estimates for each of the original distributions were made. The estimated distributions were then used to define the needed values for the calculations of the *Fsym* and *Fu*. In these experiments the 4th degree polynomian fit was used. *Fig. 7* shows an example of a series of measured filler distributions (solid lines) and estimated distributions (broken lines). Values marked with squared dots (three in each picture) represent the values, and these were used to calculate the *Fsym* and *Fu* values related to each filler distribution.

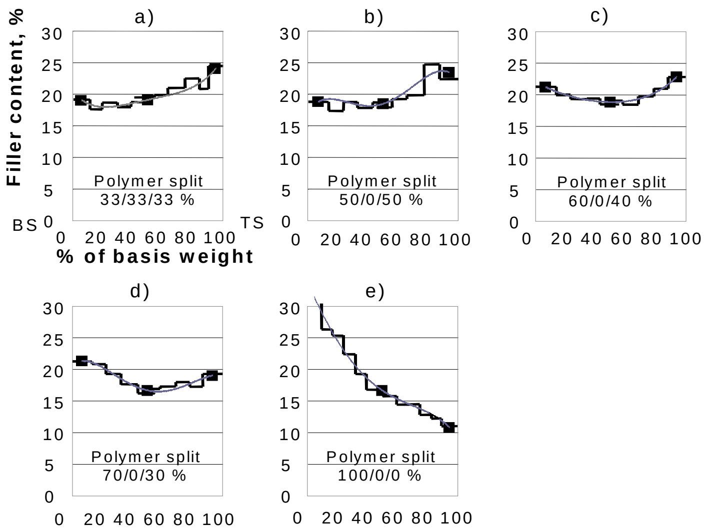


Fig. 7. Typical filler distributions at different retention chemical splits. Measured filler distributions are represented by solid lines and estimates by dashed lines. Estimates are 4th degree polynomes, 80 gsm paper.

The pictures in *Fig. 8* show a few examples for geometrical interpretation of the symmetry (*Fsym*) and the shape (*Fu*) factors.

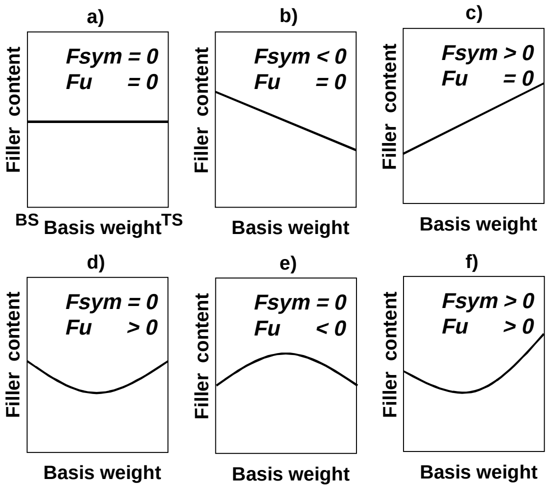


Fig. 8. Examples of geometrical interpretation of filler distribution characters, Fsym and Fu.

Fsym measures the balance between filler surface contents. When both surfaces have equal filler content, *Fsym* is 0 (a). If the bottom surface filler content is higher, *Fsym* becomes a negative value (b). If the bottom surface filler content is lower, *Fsym* is a positive value (c). The filler distribution shape factor measures the relationship between the average filler content in the surfaces and the center layer filler content. When the average filler content in the surfaces equals the center layer filler content, *Fu* is defined as 0 (a). If the center layer filler content is lower than the average filler content in the top and bottom surfaces, *Fu* is a positive value (d). Where the center layer filler content is higher than the surface layer content, *Fu* is a negative value (e). The characterization of the filler distribution is based upon a combination of these two characteristics, *Fsym* and *Fu* (f) [III].

Calculation of filler distribution estimates

In this study models for filler distributions were created and used to study the relations between the filler distributions and some quality parameters. Models were also used to calculate the relative effect of different wet end components to control the filler distributions.

The filler distribution models are based on the estimates for the filler distribution shape and symmetry factors, Fu_e and $Fsym_e$. In the following the estimates for the factors are calculated using some of the wet end control parameters. The mathematical definition of the factors can be stated in the following way:

$$Fu_e = f(Psym, Pu, Vane\ length, Q, FRvac, LBvac12) \qquad (5)$$

and

$$Fsym_e = f(Psym, Pu, Vane\ length, Q, FRvac, LBvac12), \qquad (6)$$

where *Psym* = retention chemical dosing symmetry factor,
Pu = retention chemical dosing shape factor,
Vane length = layering vane length,
Q = headbox flow rate,
FRvac = forming roll vacuum,
LBvac12 = combined vacuum of the suction boxes 1 and 2 in the LB-loading unit.

A regression analysis method was used to calculate the coefficients for the factors presented in *Equations 5 and 6*. The regression analysis design chosen was based upon the principles of one of the response surface methods, which in this case was Central Composite Surface Design. The main reason for using the chosen design was that it allowed the use of individual factors at five levels, i.e., center points, cube points and star points. The commercially available computer program that was selected allowed various experimental designs to be used. In the analysis, the statistical significance level p was set to be less than or equal to 0.05 [32].

The calculation of filler distribution estimates was based on filler distribution shape (Fu_e) and symmetry factor ($Fsym_e$) estimates, which can be calculated from the models (*Equations 5 and 6*). The estimates for filler content in the paper surfaces (Fbs_e and Fts_e) and the center area (Fcl_e) were calculated using *Equations 1-4*. Finally, in order to visualize the filler distribution estimate, the second order polynome was fitted through the calculated filler center and the surface contents. An example of such a visualization can be seen in *Fig. 9*, where the original measured filler distribution is presented by solid lines and the estimate, which was based on the model, is presented by broken lines.

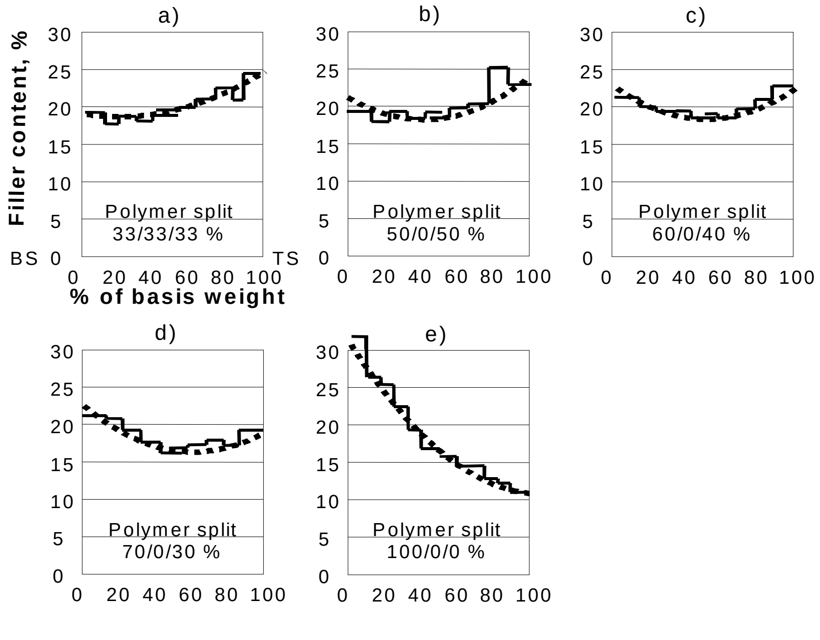


Fig. 9. Typical filler distributions (solid lines) at different retention chemical splits. Estimates (broken lines) are based on the model for 80 gsm paper.

Characterization of fiber distributions

Lloyd et al. [33] used dyed (blue) fibers in the center layer for the identification of mixing during three-layer stratified forming. A method defined as surface ply variation (SPV) was also introduced. SPV was measured by scanning samples with a photo scanner and then by analyzing these images. SPV was used to calculate the variation of the blue content of the surface within the 0.3-30 mm wave length range.

In studies performed by the author [V], parts of the center layer's long fiber fractions were dyed with a blue color in order to identify their position on the final sheet . The fibers were colored using a method developed by VTT Processes. In this method, the final dyed pulp mixture contains dyed fibers but the surrounding water remains dye-free. The portion of dyed fibers in the center layer pulp mix was approximately 25 %. The undyed pulp fraction in the center and surface layers consisted of 70 % hardwood and 30 % softwood.

The center layer fiber (dyed) deviation in the thickness direction was analyzed by laminating the final paper to separate layers in the thickness direction and then measuring and calculating the portion of colored fibers in each layer. An example of a laminated laboratory sheet made with a multilayer handsheet former [I], so that the center layer fibers are dyed blue, is presented in *Fig. 10*.

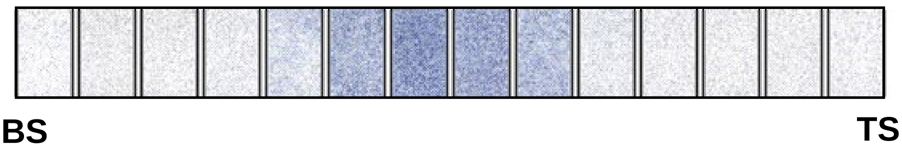


Fig. 10. Laminated laboratory multilayer former sheet, with the center layer dyed blue.

Using white and blue backgrounds CIE L* and b* color space values are determined from the layers. The distribution of dyed fibers in the thickness direction is calculated by using the L*, b* values and calibration curves. The calibration curves are used to correct layer grammage variation. In the figures, the tracer fiber distribution is presented as a function of grammage from the bottom side to the top side (*Fig. 11*). The calculation method was developed by VTT Processes.

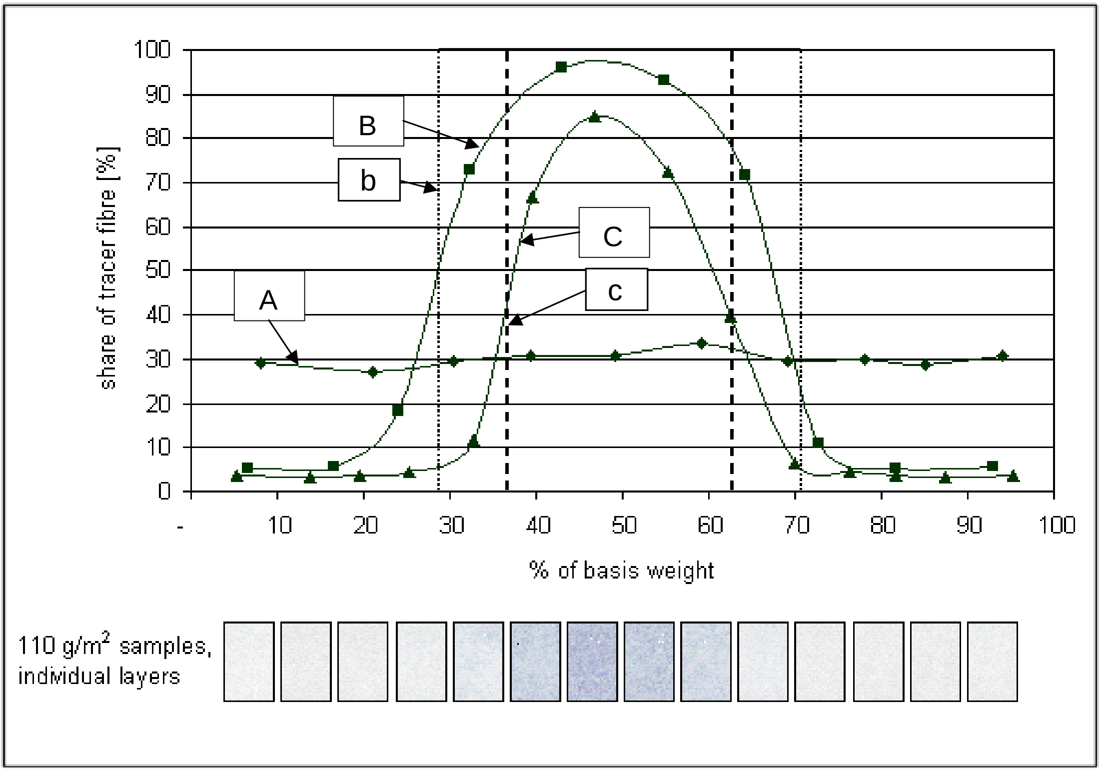


Fig. 11. The distribution of tracer fibers in laboratory-made handsheet samples.Tracer fibers are added to the center layer prior to forming. A) 70 gsm sheet where tracer fibers are applied equally to the furnish. B) 70 gsm test sheet where tracer fibers are layered in the middle layer (30 gsm). C) 110 gsm test sheet where tracer fibers are layered in the middle layer (30 gsm). The dash lines represent theoretical tracer fiber distributions in the thickness direction. b) 70 gsm sheet and c) 110 gsm sheet.

The standard laboratory measuring methods are presented in Appendix 3.

POTENTIAL OF LAYERED STRUCTURES

A number of experiments have been conducted to study and observe the potential of the method of creating layered paper samples. For the most common applications the potential is related to raw material economy and/or improved quality parameters [22,23,34-40]. Depending on the philosophy behind the layering, various advantages can be seen compared with the conventional way of making paper.

Fiber layering

Häggblom-Ahnger et al. [24] discussed the potential of multilayering office paper grades. They reported improvements in critical properties such as bending stiffness, formation and opacity. A further possible benefit would be basis weight reduction while maintaining stiffness and opacity at the same level. The reduction of furnish costs by using CTMP furnish instead of chemical pulp in the middle layer has also been discussed. One possibility is to put recycled furnish in the middle layer while retaining high quality virgin pulp on the surfaces. In studies concerning the optimum location of softwood sulfate pulp in three-ply office paper Häggblom-Ahnger [41] found that bending stiffness, formation and smoothness were improved by locating the softwood in the middle ply instead of in the outer layers. The optimum stiffness and surface properties could be achieved by using softwood and eucalyptus sulfate pulps in the middle layer and applying birch sulfate to the outer layers.

Häggblom-Ahnger [42] also discussed the fractionation of softwood sulfate pulp in three-ply copy paper. The layering of the fine fractions in the outer plies improved bending stiffness. On the other hand, by locating the fine fractions of softwood sulfate in the middle layer, Scott Bond was clearly improved.

Additives layering

Kinnunen et al. [25] discussed the role of different forming concepts and additives layering principles to control filler and fines distribution in SC paper grades. They reported that it was possible to improve optical properties by increasing surface filler content. With multilayering it seemed to be possible to achieve a small brightness increase without opacity loss. Odell [26] also discussed the advantages of multilayering. He reported significant improvements in the gloss and dot gain from the pilot printing of the multilayered SC papers when the surface filler content was increased by layering retention chemicals into the paper surfaces.

Harwood [22] mentioned the possible advantages to be gained by layering additives such as starch, filler, size and retention aids selectively, rather than dispersing them across all the paper. In three ply layering, the addition of starch to the center layer (rather than to all plies) increased tensile and bond strength.

Häggblom-Ahnger et al. [24] reported experiments with consistency layering. They noticed that consistency layering had a significant impact on formation.

A laboratory study concerning chemical layering of WFC base paper

The experiments performed by the author et al. [II] studied different possibilities to create desired surface properties by layering certain components in a WFC base paper. The study was executed on a multilayer laboratory handsheet former [I]. One of the main tasks was to reduce the openness of the paper surface through concentrating fillers on the paper surfaces. The grammage of the sheets was 80 gsm with rosette-shape PCC filler (median particle size of 1.5 µm) contents of 22%, 26% and 36%. The chemical pulp used was a 65 / 35 % mixture of hardwood kraft pulp beaten to SR° 24 and softwood kraft pulp beaten to SR° 20.

The study was based on previous findings that showed that increased filler content in paper surfaces has several beneficial effects on either metered film press (MFP) or metered size press processes (MSP). Forrström et al. [43] showed that the coat weight formed on woodfree base paper in filmpress precoating depended mainly on the coating color film on the application roll and the base paper surface porosity. Low base paper surface porosity and/or high filler content on the surface of the sheet decreased coating color penetration into the base paper structure and the coating color stayed better on the surface. Grön et al. [44] studied LWC base on a metered film press (MFP) process. The main findings were that, when coating color is transferred to a base paper, a paper with high filler content demanded less premetered film to achieve the desired coated paper properties. In particular, base paper with the highest filler content (20 %) also exhibited a denser paper surface and kept the color more effectively on the paper surface. It was shown by Ahlroos et al. [45] that increasing the base paper filler content levels had a positive effect on surface roughness, print gloss and print mottle in HSWO Printing. It was also found that coat weight uniformity was improved by pre-calendering as well as by higher filler amounts in the base paper. Studies with WFC base paper and a metered size press (MSP) by Dickson et al [27] showed that improved coating coverage can be obtained through the use of more filler in the surface of the base paper, higher levels of kaolin clay in the coating formula, lower nip load, and softer size press rolls.

In this study it was found that concentrating fillers in base paper surfaces promoted quality characteristics such as brightness and surface roughness. Surface roughness decreased and brightness increased when the filler content in paper surfaces was increased. The brightness and surface roughness change followed the surface filler content change (*Figs. 12 and 14*) rather than changes in the filler total content (*Fig. 13*). At the same time, with constant filler content, paper strength increased as the filler concentration in paper surfaces increased (*Fig. 15*).

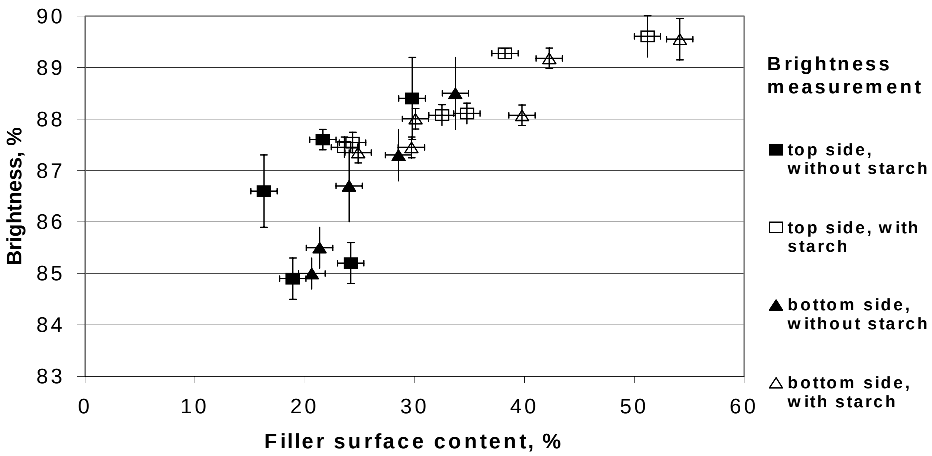


Fig. 12. Brightness as a function of paper surface filler content.

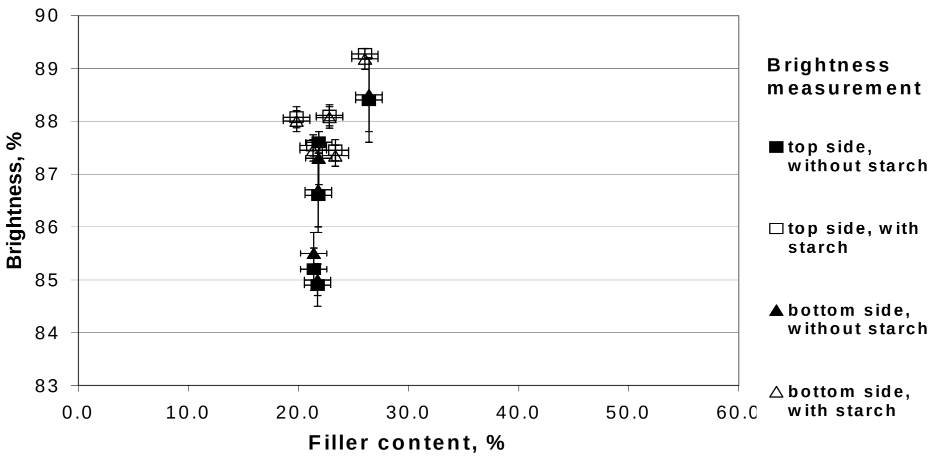


Fig. 13. Brightness as a function of filler total content.

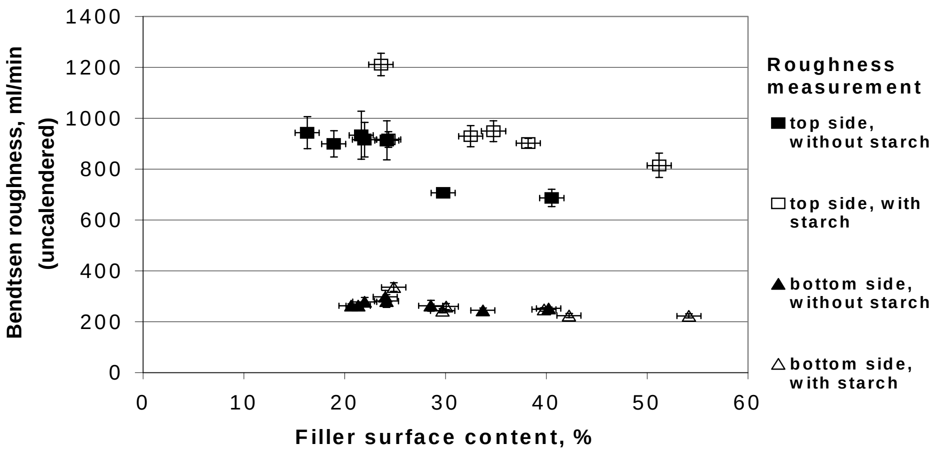


Fig. 14. Surface roughness (Bendtsen) of uncalendered paper as a function of paper surface filler content.

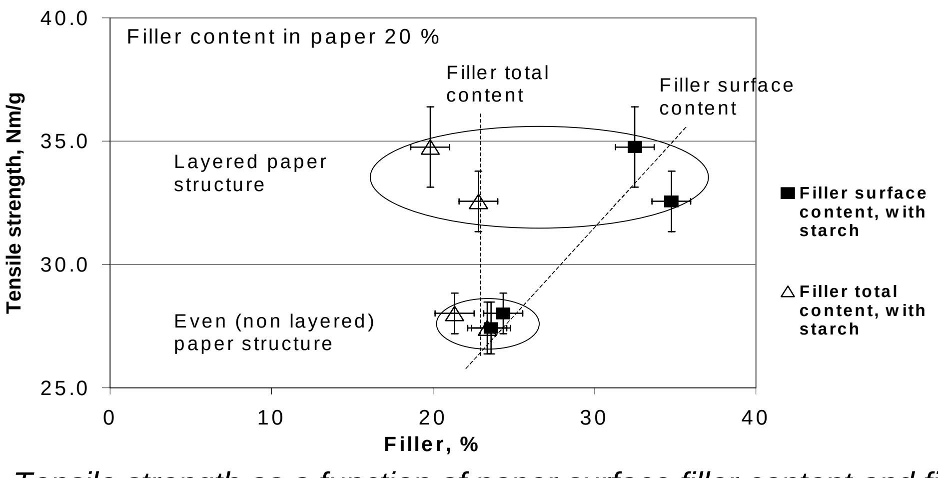


Fig. 15. Tensile strength as a function of paper surface filler content and filler total content.

Smoother base paper also showed smoother paper surface properties after coating. It was also shown that the dusting tendency of fillers in laboratory calendering could be significantly decreased by using starch. Layering offers an opportunity to intensify the use of starch by using layering techniques and targeting the starch at the paper surfaces.

LAYER MIXING

Layering with a multilayer headbox is based on the idea of separating the layers from each other as long as possible. The consolidation of the different layers takes place after the separating vanes, inside or outside the headbox. After consolidation during sheet formation, the different layers tend to mix together. Mixing of layers does occur in the free jet and continues in the various dewatering phases in the forming section.

Mixing can be different in different dewatering phases. In roll-blade gap forming during the roll dewatering phase, the water volumes are significantly bigger than in the blade dewatering phase. Thus it is concluded that the mixing is also different. Furthermore, the raw materials to be layered may behave differently during different dewatering phases. The behavior of fibers may be different than the behavior of fillers. The behavior of the fillers is also related to the retention level [28] and the retention mechanisms. Lindström [46,47] categorizes the retention mechanisms in the following way: charge neutralization, patch model of flocculation, hetero flocculation, bridging flocculation (adsorption flocculation, sensitization flocculation, complex flocculation), network flocculation and volume restriction flocculation. Depending on the dewatering phase, the retention mechanisms of fillers may vary from that of fibers and thus give space for independent movements of fillers. The goal may still be to control the layerability of both fibers and fillers.

Headbox flow and vanes

In the first stage of layer consolidation just after the vanes, mixing is governed by the hydrodynamic state of the flows to be consolidated and phenomena related to the vanes themselves.

Baker et al. [48] studied the impact of three dimensional headbox flows on tissue layer purity. They observed the existence of both spanwise and streamwise structures within the wake of headbox dividers. They stated that three dimensional flows can have a significant effect on layer purity and that the potential mechanisms responsible for such flows include the formation of swirling flows at the diffuser tube bank, three dimensional wakes formed at divider tips and instability of the free jet surface. They also found that the use of extended flexible slice lips can improve layer purity, though the mechanisms for these improvements were not identified.

Jetsu et al. [49] discussed the inherited nature and the formation of coherent structures (CS) of suspension flow when using vanes. The CS is geometrically three dimensional and can be separated into MD and CD components (which are dominant) with distinctive characteristics of their own. The amplitude and wave length of the CS was found to be related to the dimensions of the vane. By increasing the effective thickness of the vane, it was possible to increase the amplitude and wave length of the CS .

Lloyd et al. [33] studied layer mixing during three-layer stratified forming. They concluded that a combination of vane tip vortices and channel turbulence is thought to cause significant mixing of the different layers during stratified forming. Shorter vanes led to mixing at floc level, while longer vanes produced mixing at the fiber level. Longer vanes in a contracting nozzle meant higher flow velocities, both at the vane tips and in the flow channels. This was thought to produce more intense and smaller scale turbulence, which tended to mix the layers more at the fiber level than at the floc level. Very long vanes caused complete turbulent mixing of the different layers and very poor sheet formation. The other study done by Lloyd et al. [50] concerned the effect of vane shape on layer mixing. They used stepped vanes with various configurations. The aim of the steps was to break down the boundary layers formed upstream along the vanes, and thus reduce downstream vortex generation. They noticed that the turbulence introduced by the steps increased the layer mixing.

Lepomäki et al. [51] suggested that it is important to keep the amplitude of coherent structures in a headbox low enough for stochastic turbulence to break and obscure them. The amplitude and frequency of coherent structures are always a function of a specific dimension of the element generating them. For this reason, all disturbances, such as steps, have to be minimized after fluidization.

Li et al. [29] recommended a vane sheet with a tip thickness of 0.5 mm for 2-layer and 3-layer stratification applications. For a very thin divider sheet, it is anticipated that that there will be some concerns about cross machine uniformity problems and the sheet life.

Söderberg et al. [52] studied the influence of the contraction ratio on headbox flow, using dyed fibers in different layers. As a side result [53] they found that the optimum contraction giving the lowest layer mixing was somewhere between the low and high contraction cases.

Andersson [30,31] presented layering results achieved with a layering headbox using “air-wedge” technology. Rigid layer separator vanes terminating outside the slice opening made it possible to run different individual jet velocities in different layers. It was found that the optimum layer purity was achieved with a jet velocity profile such that the highest velocity of the jet was on the forming roll side.

Parsheh [54] studied mixing in a liquid jet out of a stratified headbox by using a model. He found that the relative difference of the vane length and the contraction length was one of the most important factors. Moreover, a vane shorter than the contraction results in the lowest mixing.

Free jet and jet impingement

The second critical stage in layer mixing is the free jet. Li et al. [29,55] studied the mixing characteristics of a water jet as a function of the distance from a stratified 2 and 3-layer headbox nozzle. They put salt water into the middle layer and measured the fluid conductivity profile in the z-direction. A mixing intensity at a specific location in the free jet, I_{MH}, was introduced. I_{MH} increased with distance from the slice, and was inversely affected by slice opening and headbox flow rate. It was found that a shorter divider sheet stickout tended to provide a lower degree of mixing. However, a longer divider sheet stickout may be preferable for the situation with a shorter free jet length.

The role of the impingement of the jet between fabrics in roll-blade forming, particularly from the layer mixing point of view, has not been discussed widely. However, it is known to be a critical part of the paper forming process.

Roll dewatering

Studies done by the author [V] with 3-layer headbox using dyed fibers showed that layer mixing increased when the headbox flow was increased (*Fig. 16*). In the graph the vertical axis shows the headbox flow increase, i.e. in all points labeled A, headbox flow was low. B denotes medium headbox flow and C high headbox flow. The horizontal axis shows the forming section dewatering intensity. In the first column from the left (denoted by 0) the dewatering of the LB-loading unit was minimized. Only minimum vacuums in the LB-loading unit vacuum boxes were used and only a pre-loading blade was used. Moving from the first to the second column (denoted by 1) and further to the third column (denoted by 2), the relative share of LB-loading unit dewatering (blade dewatering) increased at a given headbox flow.

A change in blade dewatering intensity did not have an effect on fiber mixing. Blade dewatering intensity was changed from zero blade force and minimum vacuums in the LB-loading area to maximum blade force and maximum vacuums. On the other hand Li showed that the mixing intensity at a specific location in the free jet, I_{MH}, was inversely affected by the slice opening and headbox flow rate [29]. So it was concluded that fiber mixing due to increased headbox flow took place at the roll dewatering phase.

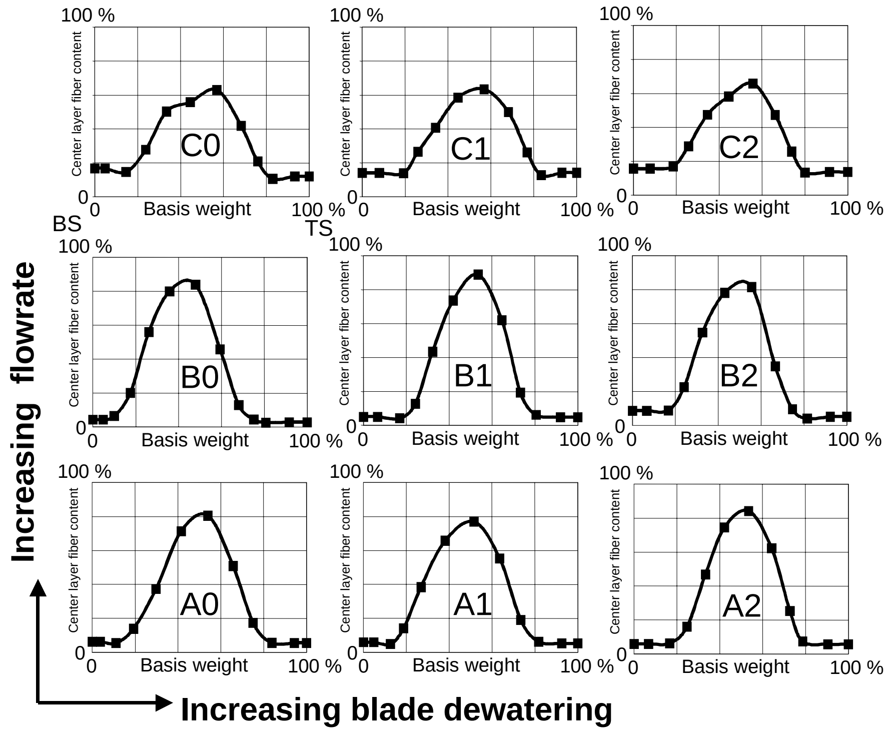


Fig. 16. Distribution of the center layer fibers.

The distributions were relatively symmetrical, and with low and medium flow rates the layer purity of the surface layers was significantly better than with a high flow rate. Approximately 20 % of the total basis weight in both surfaces remained unmixed (low and medium headbox flows) or mixing was constant (high headbox flow).

The impact of roll dewatering on the behavior of filler distributions has been discussed in the studies [III,V] performed by the author. The role of the headbox flow in the control of the filler distributions depends significantly on the basis weight. Using the definition of the filler distribution shape and symmetry factors, it was found that with 80 gsm paper, the correlation between shape factor and headbox flow was significant, whereas with 50 gsm paper it was negligible. The explanation for that is assumed to be due to the differences in the web structure after initial build up of the surface layers in the roll dewatering phase.

With 80 gsm paper, the filler distribution u-shapedness increased as a function of increased flow, i.e. the filler movement was emphasized when the headbox flow was increased. This gives an indication (first assumption) that after the creation of the surface layers, a consistency profile builds up between the surface layers. This firstly allows filler movement during dewatering after initial mat build up and secondly filler particle entrapment in the formed surface mats. The second assumption is that before a surface layer can act as a filter and the creation of a consistency profile is possible, a certain number of fiber layers (layer thickness) are needed. For papermaking fibers the basis weight of one single fiber layer is 5-10 gsm [56,57]. 50 gsm paper has approximately 20 gsm fibers per side (fillers excluded), so the theoretical number of fiber layers per side is 2-4. In their studies Wildfong et al. [58] found that the viscous resistance coefficient increased as the mat formed. They also found that at lower basis weights the increased fines level did not have a significant impact on the resistance values, presumably due to the low initial retention present during early mat deposition. An increase in the viscous resistance coefficient with fine paper furnish as well as with newsprint furnish could be seen after 20 gsm of material had been deposited.

Based on the second assumption and Wildfong's findings, it is concluded that after initial mat formation with 50 gsm paper, no excess material for consistency difference creation between layers remained. Thus a not measurable amount of free filler movement took place after initial mat formation and the impact of headbox flow on the filler distribution shape factor remained insignificant. This is probably also the reason why the effect of the former parameters on the 50 gsm paper shape factor remained insignificant.

Blade dewatering

Fiber mobility is related to layer mixing, the main part of which takes place in the headbox, jet and forming roll. Fiber mobility during the blade dewatering phase is generally related to formation improvement. Filler distribution shapes are also connected to layer mixing, particularly when filler loading into various layes has been boosted with retention chemical layering. On the other hand fillers may still have mobility when fibers have already settled into their final positions in the paper structure. Mobility differences between fibers and fillers may be at their greatest particularly in the blade dewatering phase in roll and blade dewatering.

Zhao et al. [59] studied the effect of consistency on pressure pulses in blade gap formers. They stated that to improve formation, relative movement must take place among the fibers so that the fibers move from the flocs to the zones between the flocs. Thus, the fiber displacement distance should be of the order of a floc diameter if formation is to be affected in a significant way.

Nordström et al. [60] showed that the effect on formation of a change from roll to roll-blade dewatering was found to be determined by a balance between improving and impairing mechanisms. This balance was influenced by jet quality and blade force and was different in different wave length ranges. Higher blade forces led to a deterioration in both the small-scale and large-scale formation. Norman [61] stated that the effects of dewatering pulses on paper properties are positive as well as negative. The main positive effect is the improvement of large scale formation. The effect of the blade pulses is larger the poorer the formation level after initial roll dewatering.

Kerekes et al. [62] presented two aspects of a fiber suspension which determine the degree to which it may lead to good formation - uniformity and mobility. A uniform suspension tends to produce good formation. Mobility, meaning the ease with which fibers can move relative to one another, also affects formation. A crowding factor, N, defined as the number of fibers in a spherical volume of diameter equal to the length of the fiber, has been used to characterize flocculation of fibers in a water suspension. The mobility of fibers and their uniformity of distribution were shown to change dramatically over the range 1<=N<=130. At N~=1, fiber mobility was high. As N>1, the suspension tended to become non-uniform for fibers with a high-aspect ratio (length/diameter) and uniform for low-aspect ratios. In the range 60<=N<=130, fiber mobility decreased significantly. Kerekes et al. [63] stated that both fiber length and coarseness also affected fiber mobility. It was postulated that, like uniformity, mobility is a key factor in formation, since it determines the extent to which suspension uniformity can be altered during drainage on the paper machine. In layer mixing studies performed by the author [V] it was found out that layer mixing increased when the headbox flow was increased (*Fig. 17*). On the other hand it was also found that surface uniformity two-sidedness started to gradually worsen when the headbox flow was increased and that the top surface became more uniform. On the bottom side, surface unevenness increased and, at the highest flow rate, clearly observable faults (crushing) could be seen. The flow level, which caused visible unevenness in the paper, was chosen consciously and was here considered to be "high" headbox flow. *Figs. 17* and *18* show the scanned pictures of the paper bottom and top side surfaces. Dyed fibers in the paper center layer were used. The crushing originated most probably in the roll dewatering (gap) area. In the C0 case, the following dewatering treatment (after the roll dewatering phase) was very gentle, particularly on the bottom side (*Fig. 17*). The reason for crushing is assumed to be the too fast densification of the fiber mat after a certain threshold headbox flow during the initial dewatering phase. This led to uncontrollable suspension flows in the paper surface plane directions, resulting in visible fiber clumps.

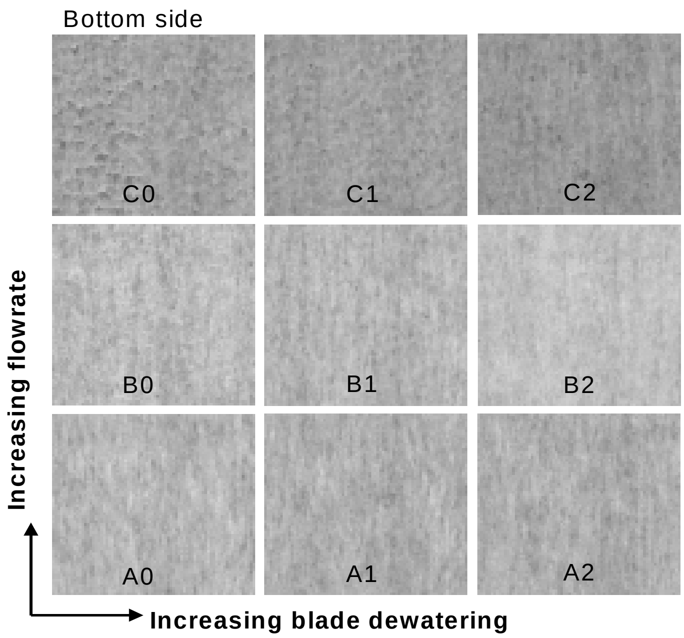


Fig. 17. Scanned bottom side surfaces at various trial points. Dyed fibers used in the center layer.

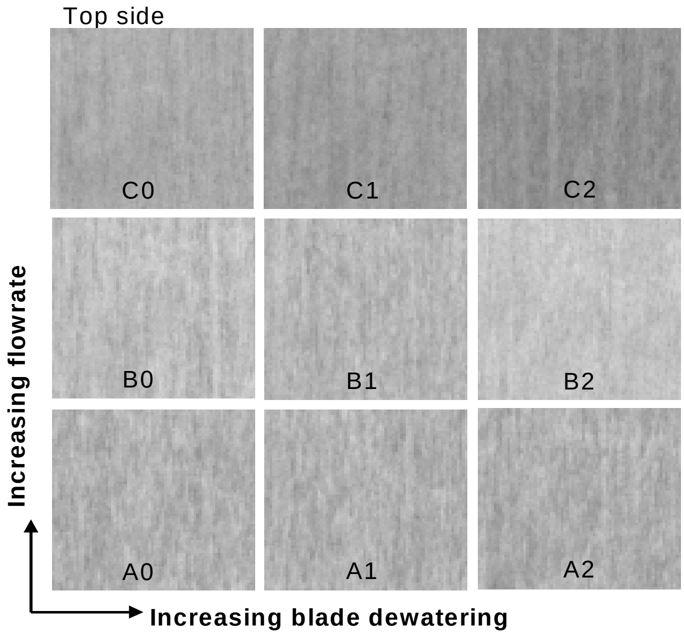


Fig. 18. Scanned top side surfaces at various trial points. Dyed fibers used in the center layer.

The area of disturbance in the paper thickness direction can be visualized by means of the following figure (*Fig. 19*), where the scanned pictures of all the separate paper layers in cross direction at various test points are presented. The formed sheets were typically divided into 8-10 individual plies in the paper thickness direction. The paper splitting technique used was the same as for the filler distributions assessments. Each picture in *Fig. 19* is composed of scanned pictures of each individual plies (width 50 mm). In final picture the plies are arranged side by side according to their position in paper thickness direction resulting a picture which represents the paper's z-directional structure. The pictures were prepared from the undyed samples. The uneven pattern in the bottom surface of the paper (in the paper thickness direction) can be seen in figures B0, B1, C0, C1 and C2. It is relatively easy to make a distinction between the crushed areas and the floccy areas by visually inspecting *Figs. 17, 18* and *19* at the same time.

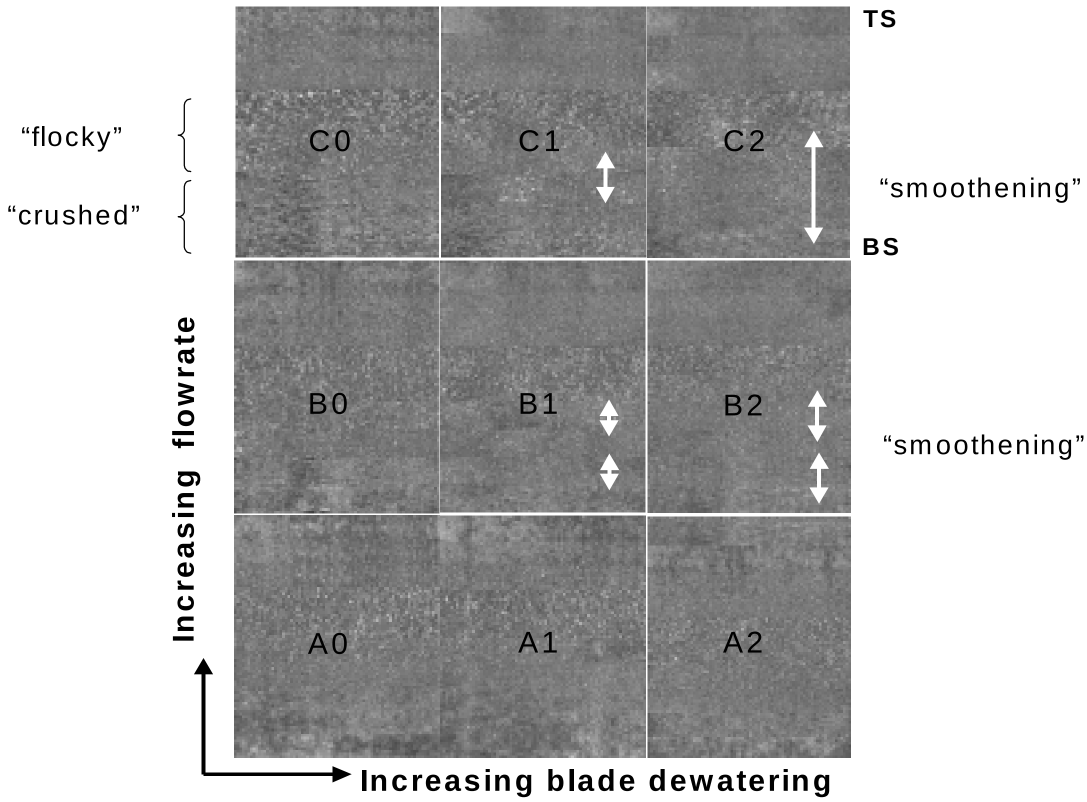


Fig. 19. Scanned layers at various trial points. In each picture (A0, A1, ..), representing a single trial point, pictures of each individual ply have been ordered according to their positions in the paper's thickness direction. Each picture typically consists of 8-10 individual plies.

The bottom side unevenness (crushing) can also be seen in the floc size distribution charts in *Fig. 20*. Floc size distribution in the thickness direction of the paper was determined from the images of each layer using FFT-transformation. RMS (Root Mean Square) values were calculated from the wave length bands 0.2 – 1.0 mm, 1.0 – 10 mm and 10 mm – 100 mm from Fourier Power Spectra. Floc size is estimated to be half of the wave length. A small RMS value indicates a low amount of flocs while, correspondingly, a high RMS value means a high number of flocs.

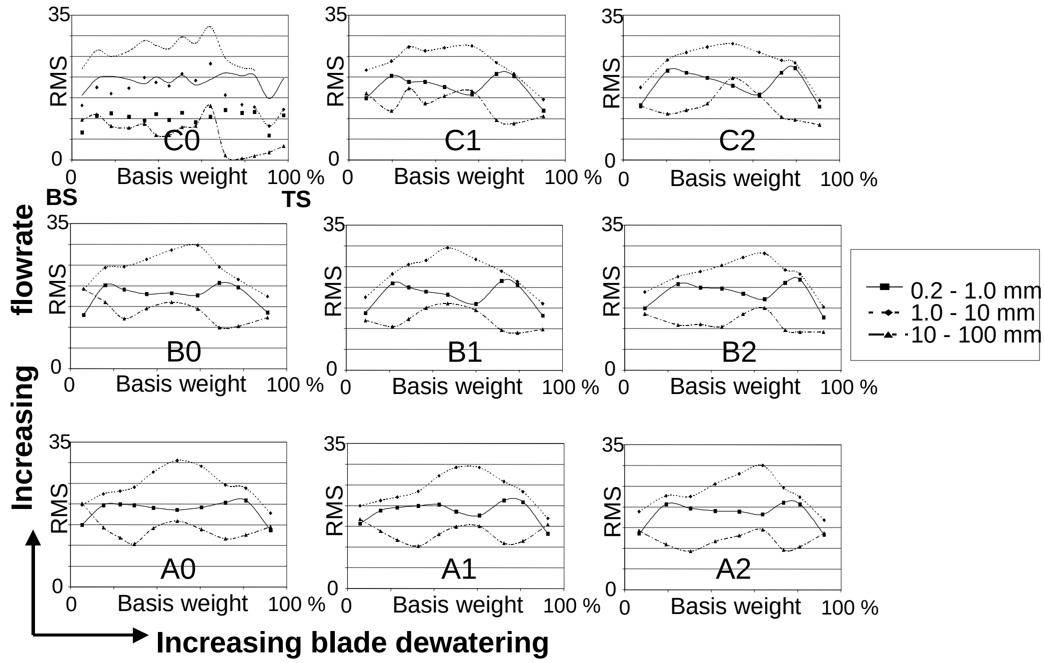


Fig. 20. Floc size distributions. Floc categories 0.2-1 mm, 1.0-10 mm and 10-100 mm.

When estimating the role of the LB-loading unit in improving formation characteristics, changes in floccy and crushed areas of the paper structure can be used as a "tracer" of changes made by the LB-loading unit. If the structure is "smooth", the deflocculation power of the LB-loading unit cannot be identified using paper samples even if the pulsation created by the LB-loading unit is strong enough to break the flocs [61].

Fig. 19 shows that when the blade dewatering intensity is increased, floc breaking (and smoothing of the crushed structure) starts first inside the paper web (see changes in floccy and "crushed" areas in *Fig. 19*). The region where the floc breaking starts can be estimated to be 1/3 of the web thickness measured from the paper bottom side in case of the highest headbox flow. The floc breaking capability is also related to the headbox flow. The forming roll area dewatering remained relatively constant with different headbox flows, but the LB-unit dewatering increased as a function of increased headbox flow and blade loading intensity. Thus it is concluded that the incoming consistency of the LB-loading unit is related to the headbox flow and therefore also to the floc breaking capability.

Zhao et al. [59] showed that increased consistency in the blade section leads to increased peak pressure (picture a in *Fig. 21*). Further, according to Zhao, to create relative fiber displacement between the mat and the remaining undrained suspension, the shear stress must be higher than the yield strength of the undrained stock, but not of the formed mat. Bennington [64] showed that the yield stress of the undrained suspension depends strongly on the consistency. Using Zhao's findings, it is possible to explain the behavior of floccy and crushed areas due to blade forces by introducing the assumption of a consistency profile of the web in some phase of the LB-loading unit. This hypothesis of the floc breaking power of the LB-unit could be stated according to *Fig. 21*.

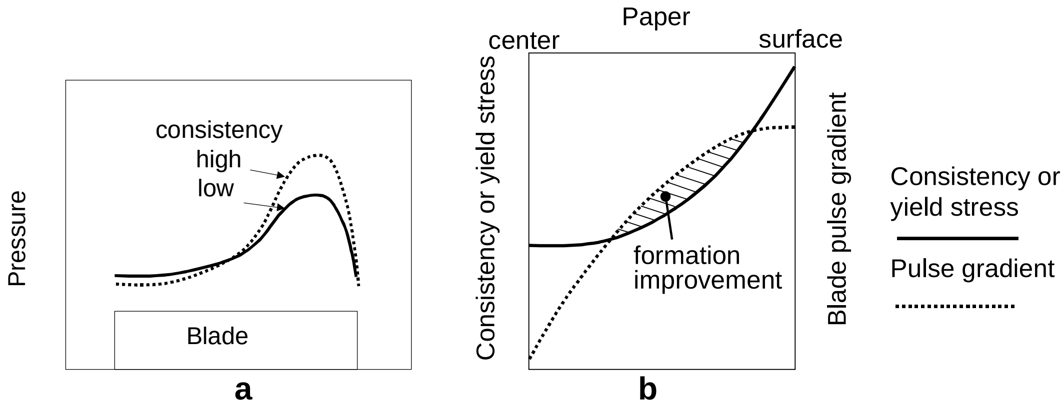


Fig. 21. a) The effect of web consistency on blade pressure (Zhao et al.). b) Hypothetical relationship between web consistency, blade pulse intensity (blade force) and steepness (gradient) in terms of the floc breaking capability of the LB-loading unit.

The capability of the LB-loading unit to break flocs (improve formation) is related to the blade pulse intensity (blade force), steepness (gradient) and web consistency at given positions in the paper thickness direction. Picture b in *Fig. 21* shows a hypothetical situation (consistency/yield stress of the undrained suspension and pulse gradient) at the moment of peak pressure (picture a in *Fig. 21*). On paper surfaces, due to the higher consistency, blade peak pressure is higher than in the paper center area where consistency is lower. This means that the pressure pulse gradient (rate of change) decreases when approaching the paper center area. The higher the consistency difference between the surfaces and the center area is, the bigger the change in pulse gradient. On the other hand it is known that in order to be able to improve formation in the blade section, the consistency has to be low enough. With a combination of proper consistency profile and blade pulse intensity and gradient, the area where formation improvement is possible can be found. With low basis weights it is assumed that the role of the consistency profile is diminished and the floc breaking capability is related only to the blade pulse intensity and pulse shape. According to the hypothesis, in the case of a straight consistency profile the pulse gradient is also the same straight across the paper web.

It was also shown that filler distributions can be significantly affected during the blade dewatering phase, with the mobility of fibers simultaneously remaining insignificant. *Fig. 22* shows that the headbox flow has a strong influence on filler distribution. On the other hand it is also shown that significant changes in filler distribution result from changing the blade dewatering intensity.

The process of modeling the filler distributions by characterizing the filler distribution symmetry and shape factors by means of the general wet end controlling parameters has already been introduced in this paper. Filler distributions can also been modeled by using only relative dewatering numbers: forming section total dewatering related to the case A0 (lowest headbox flow and minimized blade dewatering) and forming area dewatering two-sidedness value (TS/BS). The mathematical definition for the estimates of the characters, Fu_e and $Fsym_e$, can be stated in the following way:

$$Fu_e = f(\text{total former dewatering, dewatering two-sidedness (TS/BS)}) \quad (7)$$

and

$$Fsym_e = f(\text{total former dewatering, dewatering two-sidedness (TS/BS)}). \quad (8)$$

Using the estimated filler symmetry and shape factors and *Equations 1-4*, the estimates for top, bottom and center filler contents can be calculated, and further estimates can be made for the filler distributions. The original and estimated filler distributions are presented in *Fig. 22*. Solid lines represent the original filler distributions and dashed line the estimates.

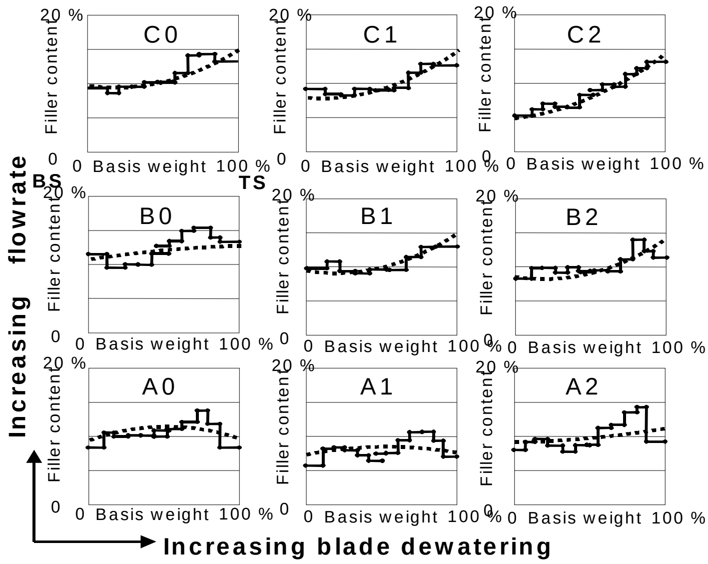


Fig. 22. Original filler distributions (solid lines) and estimates (broken lines). The estimates are based on model. 80 gsm paper.

Results show that the forming section dewatering numbers determine the filler distribution characters relatively well. The tests were performed with 80 gsm fine paper.

The shape factor responded similarly to the headbox flow rate changes as was the case in the other study [III] performed by the author. The correlation of forming section parameters with filler distribution shape characters was less significant with 80 gsm paper, because the vacuum adjustments in the LB-loading unit were limited and trials were performed with constant blade pressure.

THE USE OF ADDITIVES LAYERING AS A PART OF PAPER QUALITY CONTROL

Paper quality requirements depend greatly upon the end users' needs. Requirements for coated base papers can differ significantly from those for copy papers. Base paper quality parameters such as porosity and surface roughness are important factors affecting the quality of coated paper. The correlation between the smoothness of base paper and the smoothness of coated paper is clear. Base paper properties should also be symmetrical in order to avoid the need for asymmetrical treatment of the base paper [65-67]. High base paper surface filler content decreases coating color penetration into the base paper structure and the coating color stays better on the surface [43-45]. For copy paper grades the ideal filler distribution needs to be symmetrical and the surface filler content lower than the average filler content to reduce dusting [24,26].

It has been shown that dewatering conditions during drainage are responsible for the movement of fines and fillers in the thickness direction of a sheet [III, 24-26,65], while later process phases, such as pressing, no longer have a significant effect on filler distributions [68]. The role of different forming concepts on the control of fines and filler distributions can vary. Fourdriniers show low fines and filler content on the wire side. Hybrid formers reduce top side fines and filler content which results in a more symmetrical distribution in which the filler is concentrated in the center of the sheet. Gap former results show that the fines and filler distributions are symmetrical and more or less U-shaped [25].

Even if the importance of the z-directional distribution of fillers and fines on paper quality has been noted, less attention has been paid to how to control the distributions. In many cases multilayering has been considered for its potential to improve some paper quality properties. Less attention has been paid to the role and use of the multilayering process as a tool in the control of critical quality parameters. This is important, particularly in those cases when other process variables are also present.

In the study performed by the author on fine paper [IV], one of the main goals was to find out whether there is any relationship between filler distributions and other paper quality parameters. The study was done by using a 3-layer headbox and roll and blade gap former. Wet end additives layering principles were used to control the filler distribution together with the normal headbox and former running parameters. The models were created and used to study the relations between the filler distributions and the chosen quality parameters. The parameters were extracted from the pilot paper machine trial results using a statistical approach. The quality parameters chosen in this case were formation, porosity and oil absorption two-sidedness. The main focus of the study was on 50 and 80 gsm woodfree papers.

Estimates

The calculation of filler distribution estimates was based on *Equations 5 and 6*. The next step was to calculate the estimates for the porosity ($Poro_e$), formation index ($Forma_e$), and oil absorption two-sidedness ($Oilab_e$). The mathematical definition for the factors can be expressed in the following way:

$$Poro_e = f(Psym, Pu, Q, FRvac, LBvac1, LBvac2), \quad (9)$$

$$Forma_e = f(Psym, Pu, Q, FRvac, LBvac1, LBvac2), \quad (10)$$

and

$$Oilab_e = f(Psym, Pu, Q, FRvac, LBvac1, LBvac2), \quad (11)$$

where *Psym* = retention chemical dosing symmetry factor,
Pu = retention chemical dosing shape factor,
Q = headbox flow rate,
FRvac = forming roll vacuum,
LBvac1 = vacuum level of the lower suction box in the LB-loading unit,
LBvac2 = vacuum level of the upper suction box in the LB-loading unit.

A regression analysis method (Central Composite Surface Design [32]) was used for the calculation of the coefficients for the factors presented in equations (9), (10) and (11). In Appendix 6 has been shown the estimated vs. measured, porosity, formation index and oil absorption two-sidedness for both 50 and 80 gsm papers.

The results showed a clear dependence of the quality factors in question on the filler distribution characteristics. Formation improvement and densification of the paper were achievable at the same running conditions. The strong correlation between formation and porosity can be seen in *Fig. 23*, where all the 80 gsm paper beta formation values have been plotted against porosity values. In the picture, beta formation index is prepared by dividing the measured beta formation value by the square root of the sheet's basis weight in that particular point. The figure is made using the original measured data.

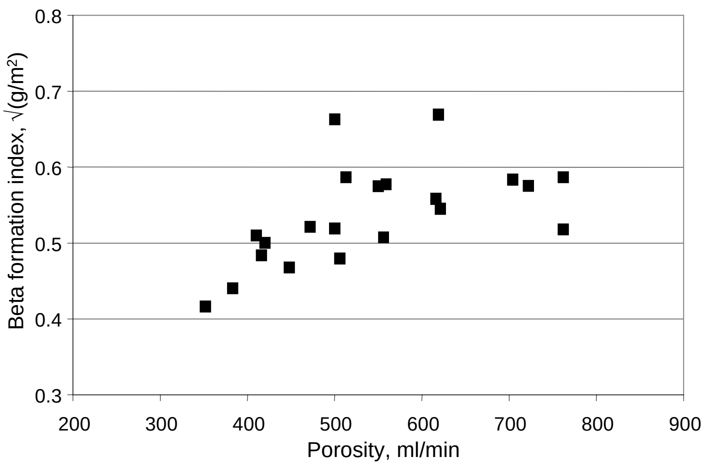
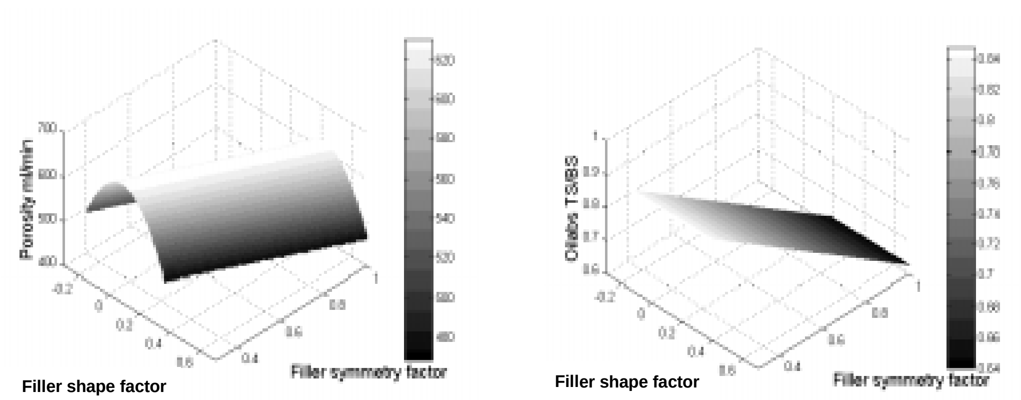


Fig. 23. Beta formation index as a function of porosity (Bendtsen). 80 gsm paper.

Low porosity favored evenly distributed constituents (good formation) and a local rich filler concentration somewhere in the paper structure in the paper thickness direction (*Fig. 24a*). Figure shows all combinations of the filler distribution characteristics that are possible when the flow rates and former vacuums are stepped within their operating range.

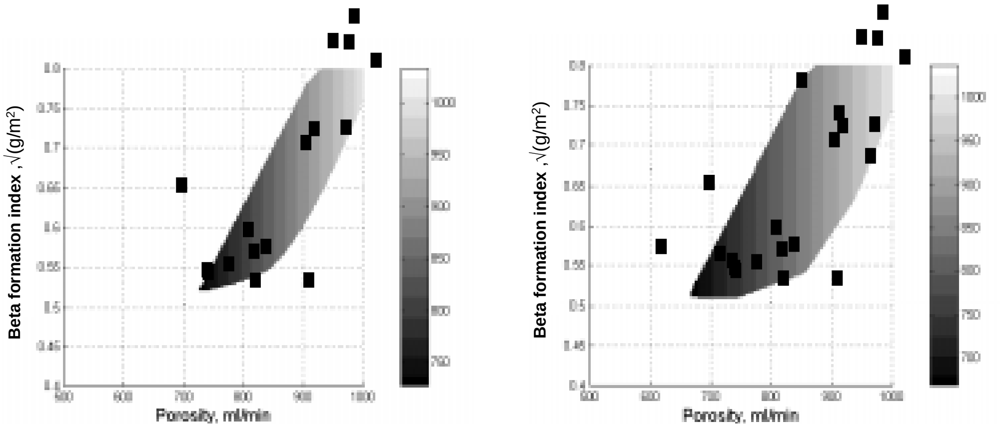
The oil absorption two-sidedness minimum favored symmetrical filler distributions (*Fig. 24b*). The optimum regions could be found in the area in which the filler distribution symmetry factor had its minimum value, i.e. when the difference between filler surface contents in the filler distribution was minimized. The optimum value was, in practice, independent of the shape (factor) of the filler distribution.



a b

Fig. 24. a) Porosity (Bendtsen) and b) oil absorption two-sidedness as a function of filler distribution shape and symmetry factors. 80 gsm paper.

Multilayering was found to be an effective tool for the control of filler distributions. On the other hand it was shown that to get optimized impact on quality properties, control of the other process variables is also needed. However the correct use of multilayering can be used to expand the field of solutions. *Fig. 25* shows an example of all possible formation and porosity combinations achievable using headbox and forming section parameters within a certain range a) without and b) with the use of multilayering. It can be seen that, for example at a given formation level, the use of the additives layering principle for the control of filler distributions makes lower porosity numbers possible.



a b

Fig. 25. Beta formation index as a function of porosity (Bendtsen). a) Retention chemical equally distributed. b) Retention chemical dosing shape factor corresponded with a split change from 30/40/30 % to 43/14/43 % (bottom/middle/top side) and split symmetry factor corresponded with a split change from 26.7/33.3/40% to 46.7/33.3/20%. Squares represent the original data points. 50 gsm paper.

CONCLUSIONS

In this study the main focus was on layering fine paper with a 3-layer headbox and roll blade gap former. The study consisted of methodological development and layering studies on a laboratory scale as well as on a pilot paper machine scale. Studies concerning the potential of layered structures in papermaking and the phenomena affecting layer mixing were performed.

The studies showed that filler distribution shape and symmetry factors correlate clearly with certain quality parameters of fine papers, such as porosity, formation and oil absorption two-sidedness. Low porosity was achieved in cases in which the paper had good formation (evenly distributed constituents) and a filler distribution characterized by local rich filler content (increased filler concentration) somewhere in the paper’s cross-section. Oil absorption two-sidedness could be minimized by a filler distribution that was as symmetrical as possible. It was shown in multilayer handsheet former research that the layering of filler has a clear influence on paper brightness and in-plane strength properties. When the filler was layered in the paper surface layers, it was possible to affect the base paper’s surface roughness to the extent that the smoothness achieved by the layering was also visible in pre-calendering and in the coated final product.

With respect to layer mixing during the different stages of former dewatering, it was observed that different types of paper constituents behave in different ways. The mixing of the layers was different in roll dewatering compared with blade dewatering. In blade dewatering the roughest fractions, such as fibers, were mobile to the extent that formation improvement was possible – but no more. On the other hand, major changes could be obtained in filler distribution shape and symmetry factors by adjusting the blade dewatering. Based on the results, a model was created by which it was possible to explain the observations made during the study concerning the factors affecting formation improvement in the LB-loading unit of the gap former.

In summary it can be said that, given the layering technology in use it will be essential to acquire more accurate control over the behavior of all the factors affecting layering before it is possible to take a number of quality factors into account in order to achieve an overall quality optimum. This is true regardless of whether the question concerns a filler-layered product or a product in which the goal is to layer the fibers. However, there is much evidence to show that, with careful optimization, it will be possible to achieve the layering objectives without neglecting other important quality factors.

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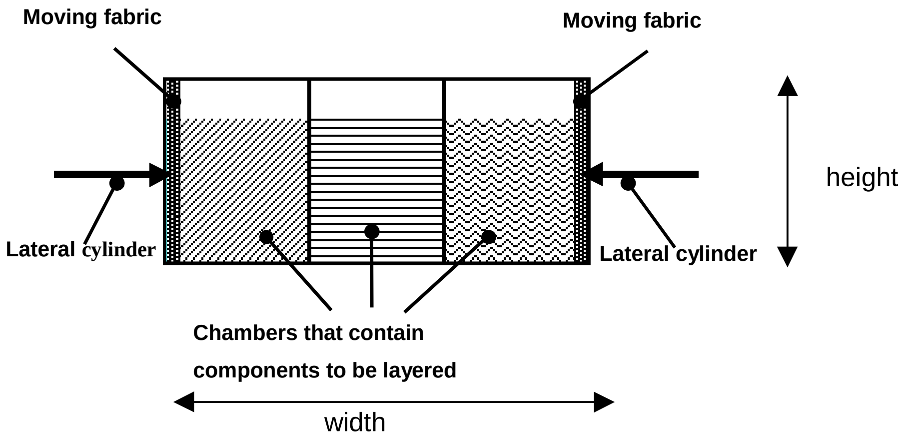
APPENDICES

APPENDIX 1

The multilayer handsheet former.



The multilayer handsheet former.

Main dimensions:
- width 750 mm , depth 250 mm and hight 345 mm

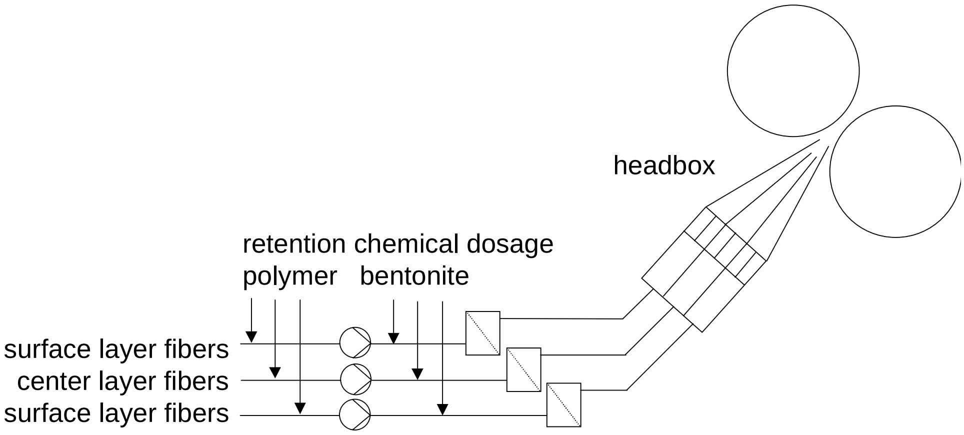
Fabric frame dimensions:
- depth 250 mm and hight 345 mm

Fabrics used:
- typical production 2-layer fabrics for newsprint grades
- air permeability 6500 $m^3/h*m^2$
- no of yarns/ cm^2: 59.5 yarns/ cm * 46.4 yarns /cm

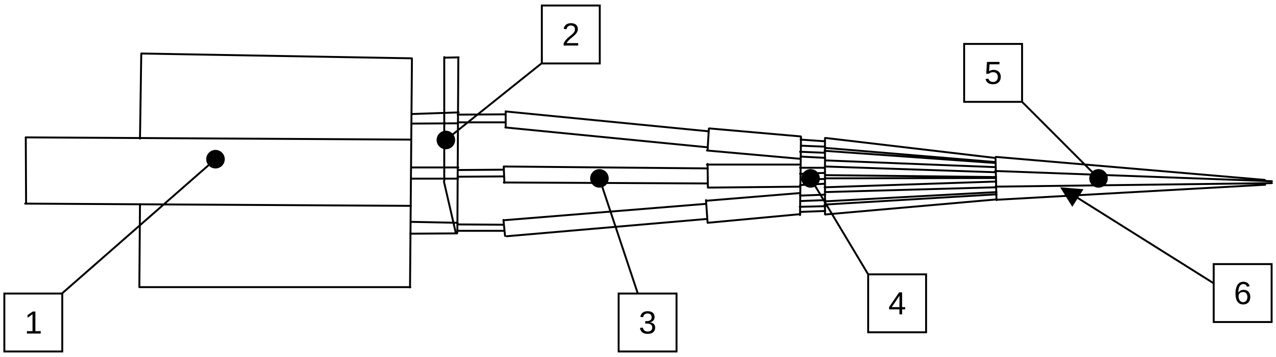
Typical process variables:
- air mixing time 15 s and intensity 100 - 150 l/min,
- air exhausting time 12 s,
- forming speed from 15 * 10^{-3} m/s to 30 * 10^{-3} m/s (movements of fabrics)
- constriction force 250 N.

APPENDIX 2 **1/4**

Test arrangements at pilot paper machine environment.



The additives and fiber layering wet end arrangements.



The 3-layer headbox.

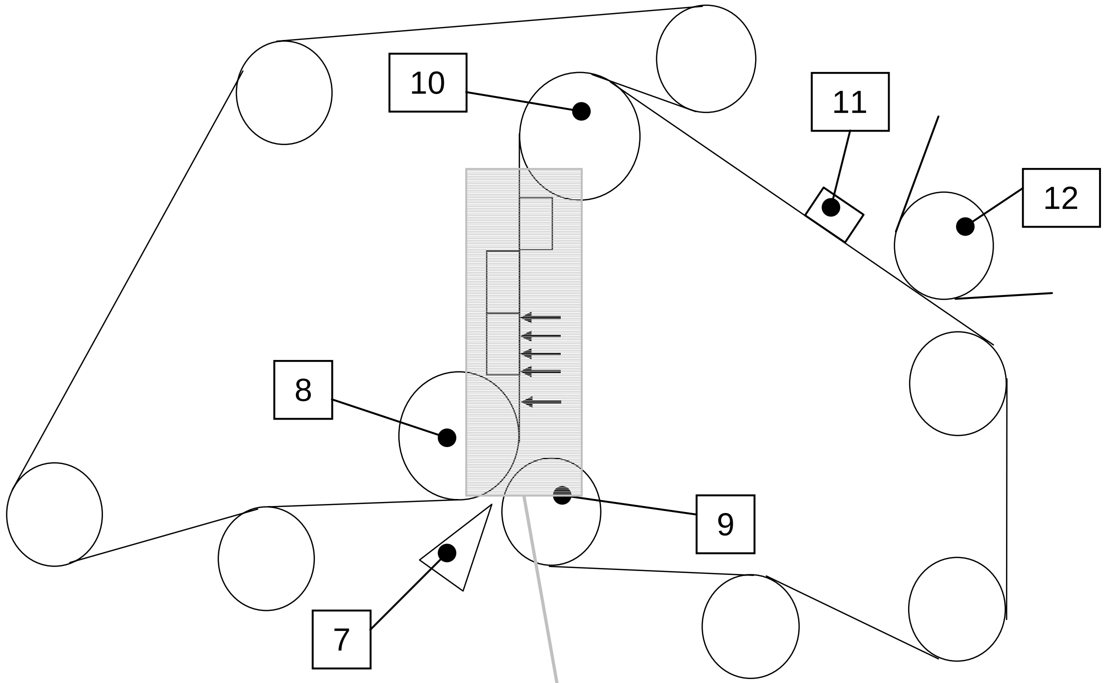
APPENDIX 2 **2/4**

Coding:

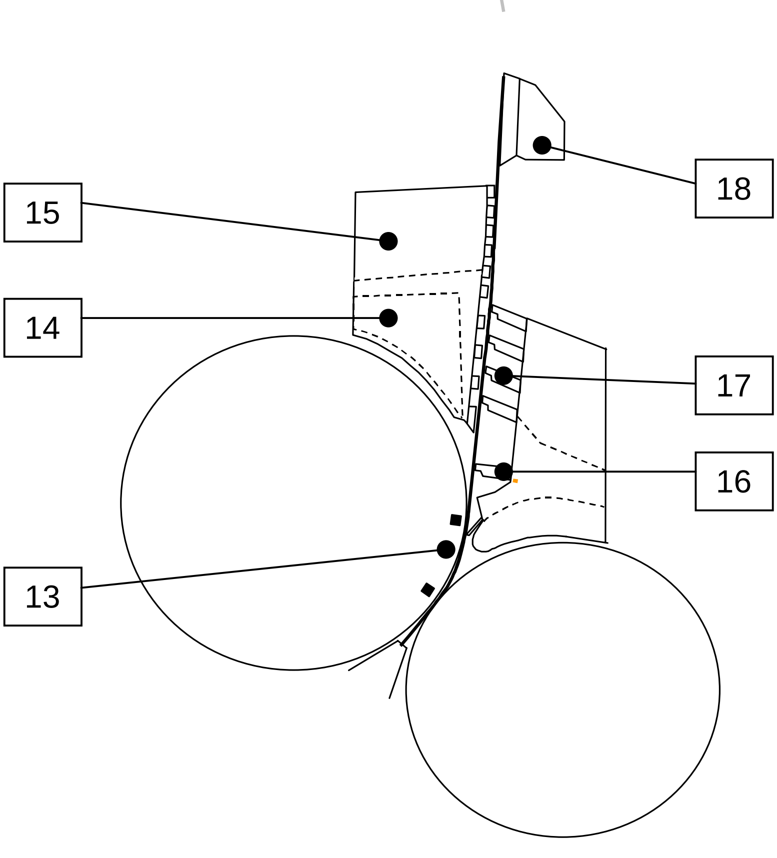
1. header
2. dilution feed
3. manifold tube bank
4. turbulence generator
5. slice chamber
6. layering vanes

Additional statistics:
- headbox slice chamber contraction 1/8..1/12 depending the slice opening
- layering vanes: 2 mm thick flexible layering vanes; the last 50 mm length of the free end (downstream end) tapered to a final thickness of 0.7 mm; sharp tip

APPENDIX 2 **3/4**



The roll and blade gap former.



The forming area of the roll and blade gap former.

APPENDIX 2 **4/4**

Coding:

7. headbox
8. forming roll
9. breast roll
10. 1st suction roll
11. high vacuum suction box
12. pick-up roll
13. forming roll vacuum zone
14. LB shoe 1 suction element
15. LB shoe 2 suction element
16. LB pre-loading element
17. LB loading elements
18. suction box

Additional statistics:

- wrap angle (the area where the outermost fabric is producing gap pressure against the forming roll) 15 ^{o}
- the radial width of the forming roll suction zone 15 ^{o}
- forming roll diameter 1600 mm
- fabrics: typical 2-layer fine paper fabrics; air permeability 5500..6500 $m^3/h*m^2$
- fabric tensions 8 kN/m

APPENDIX 3

Table 1. Standard laboratory measuring methods.

Filler content	Incineration method according to the SCAN P5:63
Furnish drainability (SR° value)	Shopper-Riegler device calibrated according to the SCAN-C 19:65
Beta formation	Ambertec beta formation tester
Oil absorption	Cobb-Unger oil absorption measuring method according to the SCAN-P 37:77
Bendtsen Porosity	Bendtsen measuring device calibrated according to SCAN-P 21:67

APPENDIX 4 **1/2**

Regression coefficients for filler distribution shape and symmetry factors, Fu_e and $Fsym_e$. Relates to the publication III: Wet end control of filler distributions using additives layering principles.

<u>50 gsm paper</u>

$Fsym_e$ = k11*Psym+k12*Q+k13*Q*Q+k14*LBvac12+k10, where

k10=26.88
k11=0.30
k12=-0.26
k13=0.00064
k14=0.020

Fu_e = k21*Pu+k20, where

k20=0.19
k21=0.030

<u>80 gsm paper</u>

$Fsym_e$ = k11*Pu+k12*Psym+k13*FRvac+k10, where

k10=0.030
k11=-0.060
k12=0.28
k13=-0.033

Fu_e = k21*Vane length(rel)+k22*Pu+k23*Q+k24*FRvac+k25*Pu*Q+k20, where

k20=-6.46
k21=0.0043
k22=0.63
k23=0.031
k24=-0.022
k25=-0.0029

APPENDIX 4 **2/2**

Regression coefficients for filler distribution shape and symmetry factors, Fu_e and $Fsym_e$. Relates to the publication V: Control of fiber mobility and filler distribution in wet end layering.

$Fsym_e$ = k11* Total former dewatering+k12* Dewatering two-sidedness (TS/BS)+ k13* Total former dewatering * Dewatering two-sidedness (TS/BS) + k10, where

k10=-2.81
k11=2.28
k12=1.86
k13=-1.41

Fu_e = k21 * Total former dewatering + k20, where

k20=-1.41
k21=1.44

APPENDIX 5 **1/2**

The headbox and former parameters related to the publication III: Wet end control of filler distributions using additives layering principles.

Table 2. Headbox and former parameters. Publication III.

	50 gsm paper		80 gsm paper	
	min	max	min	max
Polymer dose symmetry, *Psym*	-9	0	-9	0
Polymer dose shape, *Pu*	0	4,5	0	4,5
Layer vane length relative to HBX nozzle, mm	-49	+26	-49	+46
Head box flow rate, l/s*m	190	230	190	210
Forming roll vacuum, kPa	-2	0	-20	-5
LB-shoe vacuums 1&2 (combined), kPa	-25	-10	-10	0

The headbox and former parameters related to the publication IV: Controlling filler distributions for improved fine paper properties.

Table 3. Headbox and former parameters. Publication IV.

	50 gsm paper		80 gsm paper	
	min	max	min	max
Polymer dose symmetry, *Psym*	-9	0	-9	0
Polymer dose shape, *Pu*	0	4,5	0	4,5
Head box flow rate, l/s*m	190	230	190	210
Forming roll vacuum, kPa	-2	0	-20	-5
LB-shoe 1 vacuum, kPa	-10	-5	-5	0
LB-shoe 2 vacuum, kPa	-15	-5	-5	0

APPENDIX 5 **2/2**

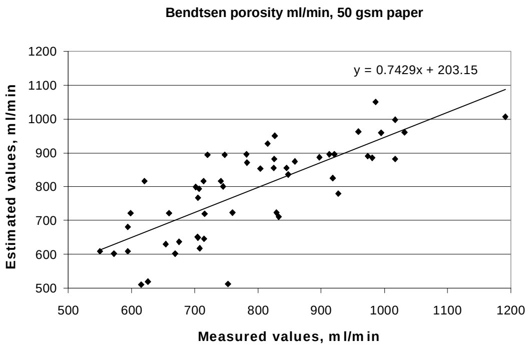
The headbox and former parameters related to the publication V: Control of fiber mobility and filler distribution in wet end layering (V).

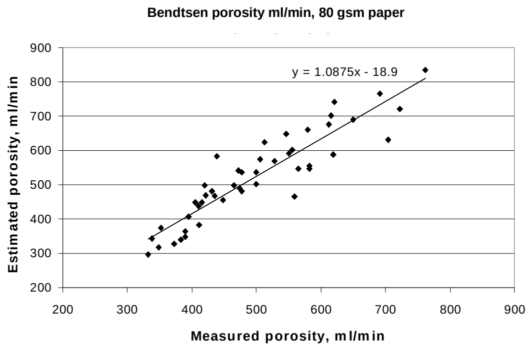
Table 4. Headbox and former parameters. Publication V.

Headbox flow rate, l/s*m	150,170,200
Forming roll vacuum, kPa	-20, -10
Loading blade load pressure, kPa	0, 10, 20
LB-shoe 1 vacuum (Lb-blades), kPa	-12, -5
LB-shoe 2 vacuum (next to Lb-shoe 1), kPa	-20, -5
Dyed fibers in center layer	not in use, in use

APPENDIX 6

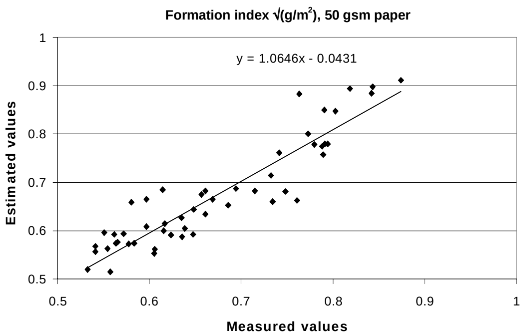
Estimated vs. measured, porosity, formation index and oil absorption two-sidedness for both 50 and 80 gsm papers. Relates to the publication IV: Controlling filler distributions for improved fine paper properties.

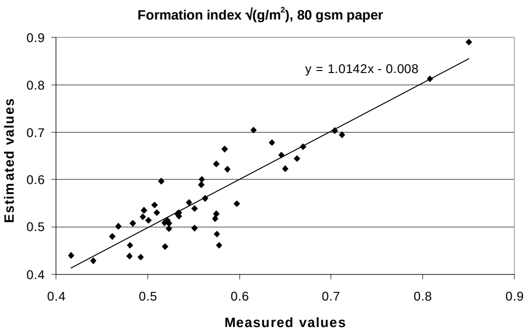




A) B)

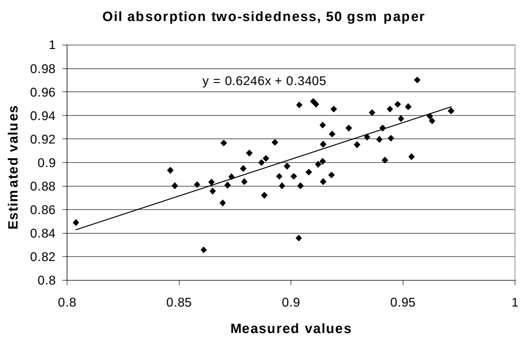
Estimated porosity as a function of measured porosity with A) 50 gsm paper and B) 80 gsm paper.

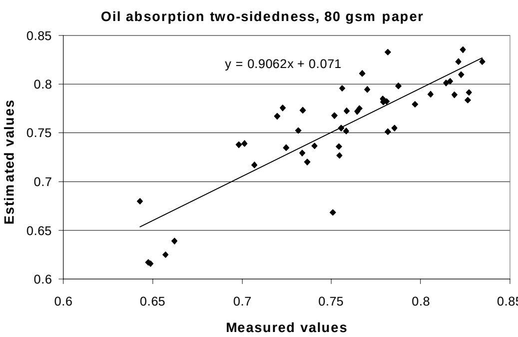




A) B)

Estimated formation index as a function of measured formation index with A) 50 gsm paper and B) 80 gsm paper.





A) B)

Estimated oil absorption two-sidedness as a function of measured oil absorption two-sidedness with A) 50 gsm paper and B) 80 gsm paper.