Tailoring Printing Paper Properties – Potential and Weakness of Mechanical Pulps in Multilayered Sheets

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ABSTRACT

A factorial design was applied to investigate and quantify the effects of layering, surface pulp quality, centre pulp quality and the weight distribution between surface and centre layers in oriented laboratory sheets. Three-layered and non-layered reference sheets were made of different mechanical pulp furnishes on a dynamic sheetformer. Surface smoothness, paper gloss, light scattering, bendability and surface compressibility were significantly improved upon layered forming, while the bonding-sensitive properties, such as tensile index, rupture elongation, TEA and especially z-directional strength declined.

The positive impact of layered forming on for example surface properties may even be enhanced by exploiting synergistic effects from optimal combinations of centre and surface layer pulp qualities. TMP accept with a low degree of splitting and low fibre coarseness performed superior in the surface of layered sheets, compared to a highly split but coarser groundwood pulp of equal fines content and freeness. However, pure laboratory sheets, made of either the groundwood pulp or TMP accept, had equal surface roughness. The importance of the centre pulp quality was verified not only for mechanical properties, such as in-plane tensile and z-strength, bendability and compressibility, but also for light scattering and surface properties.

INTRODUCTION

For the producers of high-value mechanical pulp-based printing papers, properties determining print quality such as surface smoothness, gloss, opacity, surface compressibility and surface strength are constant challenges for improvement. At the same time, the mechanical properties important for assuring good runnability on paper and printing machines should be maintained or improved. Runnability and printability set different requirements on the furnish properties. Groundwood pulps are known to promote favourable printability properties, mostly because of their high fines content and morphologic particle diversity. Standard TMP with a high proportion of long fibres are considered suitable for promoting paper strength [1,2].

An improved understanding of the role of and the interactions between fibre and fines fractions of different nature will assist in defining the optimal furnish for meeting the quality demands of a specific product. Technical solutions such as multistage refining and screening stages may then be applied to achieve the desired treatment for a specific fraction of the mechanical pulp. Simultaneously the whole fibre furnish should be optimised. The desired balance between runnability and printability characteristics may thus be achieved. However, interactions between different types of fibres are not well understood, and it is known that for instance the reinforcing potential of chemical pulp fibres in mechanical pulp furnishes is not fully utilised.

Engineering of sheet structures, with optimal layer furnish properties, seems to be a promising technology, where the potential of the different furnish constituents may be utilised better than in one-layer paper, thus achieving the desired paper and print properties [3,4]. However, while layered forming is an industrially established technology for various paper and board grades, uncoated mechanical pulp based printing papers still produced as one-layer sheet. Layering of specific fibre types has proved more difficult in printing paper production because of the problem of sufficient uniform coverage of the surface layers over the centre layer [3]. In layered forming finer particles are commonly placed in the outer layers, and coarser fibres in the central layers of the sheets. Several laboratory and pilot studies with mechanical pulps have demonstrated the potential of this type of z-directional sheet structure to clearly improve e.g. surface smoothness and gloss [5,6]. Linting and fibre rising tendency have been reported to decrease [5]. Also light scattering was found to improve somewhat upon layered forming, while strength properties were found to remain constant or to decline, especially the z-directional strength [6,7].
The main objective of this study was to establish principal knowledge as to what extent and in which direction relevant properties of layered sheets are affected by the properties, proportions and interactions of distinctive mechanical pulps in different sheet layers. This paper will specifically address significant microscopic and macroscopic differences between layered and non-layered sheets, as well as the contribution of specific mechanical pulps characteristics to layered sheet properties.

EXPERIMENTAL

Factorial Design and Statistical Analysis
A factorial design was defined in order to investigate the significance, interactions and quantitative effects on relevant sheet properties of the following variables:
- Z-directional furnish distribution (layering vs. non-layering, varied on two levels)
- Pulp and fibre quality in the sheet surface (varied on two levels)
- Pulp and fibre quality in the sheet centre (varied on two levels)
- Weight distribution between surface and centre layers (varied on three levels)

The factorial design and analyses were done with the statistical software MINITAB. Table 1 shows the variables and the levels chosen to be investigated in this study. For an introduction to the design and analysis of experiments see e.g. Box et al. [8].

Table 1: Variables and levels of the statistical design

<table>
<thead>
<tr>
<th>VARIABLES LEVELS</th>
<th>SURFACE PULP QUALITY</th>
<th>CENTRE PULP QUALITY</th>
<th>LAYERING</th>
<th>LAYER WEIGHT PROPORTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TMP screen accept (35 ml CSF)</td>
<td>TMP refined reject (80 ml CSF)</td>
<td>Non-layered (homogeneous)</td>
<td>15%/70%/15%</td>
</tr>
<tr>
<td></td>
<td>Low splitting</td>
<td>Less developed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>GW (35 ml CSF)</td>
<td>TMP refined reject (30 ml CSF)</td>
<td>Three-layered</td>
<td>25%/50%/25%</td>
</tr>
<tr>
<td></td>
<td>High splitting</td>
<td>Well developed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>35%/30%/35%</td>
</tr>
</tbody>
</table>

Selection and Characterisation of Pulps
The furnish placed in the surfaces of high-quality paper grades, such as SC-papers for gravure printing, should facilitate high smoothness, gloss, and low surface porosity in order to prevent excessive ink absorption [9]. In addition high surface compressibility is desired to assure good contact between the paper surface and the printing cylinder, and thereby achieve high print quality. For offset grades, SC-paper should have low sensitivity to water application and high surface strength in order to minimize linting, fibre rising, picking and roughening. Good dimensional stability and high bending stiffness are desirable for all grades [9].

When selecting mechanical pulps to be compared for their performance in different sheet layers, two conditions had to be met: i) the pulps should have a quality profile relevant for the target paper grades, and ii) they should be significantly different with respect to relevant quality characteristics. Pulps with a low amount of coarse fibres and a high content of small fractions and especially fines are considered suitable for high-quality printing paper. Such characteristics were provided by the screen accept from a pilot SC-grade TMP and an industrially produced SC-grade groundwood pulp, referred to as “GW 35” and “TMP Acc 35” respectively, Table 2. Both pulps had similar high fines content and equal freeness. For the centre of the sheets two refined TMP screen rejects were selected, produced in pilot scale, that significantly differed in their bonding ability. It should be noted, that both these pulps
contained fibres and fines of high conformability and bondability, Table 2. The centre pulps will be denoted as "TMP Rej 30" and "TMP Rej 80". All pulps were made from Norway spruce.

**Table 2: Mean values of pulp, fibre and fines properties of the surface and centre layer mechanical pulps**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Unit</th>
<th>Tested population</th>
<th>Surface pulps</th>
<th>Centre pulps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>TMP Acc 35</td>
<td>GW 35</td>
</tr>
<tr>
<td>CSF</td>
<td>ml</td>
<td>whole pulp</td>
<td>34</td>
<td>33</td>
</tr>
<tr>
<td>McNett R14</td>
<td>%</td>
<td>whole pulp</td>
<td>0.4</td>
<td>2.1</td>
</tr>
<tr>
<td>McNett P14/R30</td>
<td>%</td>
<td>whole pulp</td>
<td>25.5</td>
<td>11.4</td>
</tr>
<tr>
<td>McNett P30/R200</td>
<td>%</td>
<td>whole pulp</td>
<td>32.5</td>
<td>44.6</td>
</tr>
<tr>
<td>McNett P200</td>
<td>%</td>
<td>whole pulp</td>
<td>41.6</td>
<td>41.9</td>
</tr>
<tr>
<td>Fibre length? (l.w.)</td>
<td>mm</td>
<td>whole pulp</td>
<td>0.80</td>
<td>0.46</td>
</tr>
<tr>
<td>Fibre width? (l.w.)</td>
<td>µm</td>
<td>whole pulp</td>
<td>25.2</td>
<td>23.5</td>
</tr>
<tr>
<td>Fibre bendability?</td>
<td>6)</td>
<td>McNett P14/R30</td>
<td>6.35</td>
<td>4.15</td>
</tr>
<tr>
<td>Coarseness?</td>
<td>µg/m</td>
<td>McNett P14/R30</td>
<td>106</td>
<td>341</td>
</tr>
<tr>
<td>Fibre wall thickness? (10)</td>
<td>µm</td>
<td>McNett R50?</td>
<td>2.24</td>
<td>2.82</td>
</tr>
<tr>
<td>Fibre split index? (10)</td>
<td></td>
<td>McNett R50</td>
<td>0.31</td>
<td>0.70</td>
</tr>
<tr>
<td>Fibre collapse index? (10)</td>
<td></td>
<td>McNett R50?</td>
<td>0.28</td>
<td>0.26</td>
</tr>
<tr>
<td>Sedimentation spec. surface index? (11)</td>
<td>m²/g</td>
<td>McNett P14/R30</td>
<td>11.5</td>
<td>12.2</td>
</tr>
<tr>
<td>Sedimentation spec. surface index? (11)</td>
<td>m²/g</td>
<td>McNett P30/R200</td>
<td>24.8</td>
<td>23.1</td>
</tr>
<tr>
<td>Fibril content? (12)</td>
<td>%</td>
<td>McNett P200</td>
<td>37.0</td>
<td>33.3</td>
</tr>
<tr>
<td>Fines turbidity?</td>
<td>NTU</td>
<td>McNett P200</td>
<td>1363</td>
<td>745</td>
</tr>
</tbody>
</table>

1) FiberMaster 2) optical length class 1.5-3.0mm, 3) intact fibre population, 4) @ 0.1% consistency with a HACH turbidimeter

**Sheet Preparation, Calendering and Testing**

12 different series of three-layered mechanical pulp sheets and 12 series of one-layered reference sheets were produced using the Formette Dynamique dynamic sheetformer (DSF-sheets). The target grammage was 60g/m². The dynamic sheetformer produces oriented sheets with asymmetric z-profiles, due to one-sided drainage. The white water cannot be recirculated, and substantial loss of fines through the wire has been reported [6]. All sheets were formed at 1200 rpm, and dewatered for 60 seconds. Pre-trials with different retention aid combinations and amounts were conducted prior to the main experiment, in order to minimise the loss of fines. Based on these pre-studies, a combination of retention agent (Fennopol 3400) and fixation agent (Fennofix 50) from KEMIRA was chosen. The two chemicals were added separately prior to forming, with a total amount of 1.2g/kg od pulp. The same total amount of retention aids as used in the respective layered sheets was added to the mixed furnish for the non-layered reference sheets. The total fines loss of the sheets was between 1.1% and 3.5%.

The weight proportions of the surface layers compared to the centre layer were varied on three levels, Table 1. Non-layered reference sheets were produced by mixing surface and centre pulps in the same weight proportions. Non-layered sheets were made from each of the parent surface and centre layer pulps in addition. The freeness level of the furnish mixtures ranged between 29 ml and 50 ml. After draining and couching, each DSF-sheet was cut into four smaller sheets of 350cm² size, which were pressed for 5+2 min at 4.8 bar and dried restraint against a plate. 12 such small sheets from each series were immediately tested, while 2x12 sheet were calendered in a pilot calender at two different line pressure levels (75 kN/m and 225 kN/m). The sheets were conditioned before calendering (23°C/50 % RH). Calendering was performed in four nips (two against steel roll and two against soft roll) at 45 °C and 20 m/min rotational speed. Structural, optical and mechanical properties were tested according to relevant SCAN-ISO standards. Z-strength was measured according to TAPPI Tappi T 541 om-99 with a Zwick ZMART PRO instrument. Paper compressibility was assessed by two different methods: As surface compressibility (ratio of PPS surface roughness determined at 1MPa and 2 MPa) [13], and measured with a Zwick hardness tester for paper materials as thickness reduction at a given pressure. Optical and surface properties, as well as air permeability and compressibility, were tested against the inner side of the sheet.
Paper Surface Structure Characterisation

Samples of layered and non-layered calendered sheets were subjected to a laser profilometry analysis. 20 images were acquired from the inner side of the sheet with a Lehmann laser profilometer (“LLP”, IVT-Lehmann Messtechnik AG). The applied speed was 1300 (pixels/s). The samples were gold-coated previous to the Laser profilometry analysis. Gold coating prevents and reduces internal reflections and the occurrence of error heights in laser profilometry surface representations [14,15]. The image size was 2x2 mm² with a resolution of 4 μm/pixel. The topography images (Fig. 1) were processed with the SurfCharJ plugin [15] for ImageJ [16]. Paper surface characteristic details like roughness values, facet orientation (Fig. 1C) and surface pore volume (Fig. 1D) were quantified.

Fig. 1: Laser profilometry surface analysis. A) Surface representation by laser profilometry. B) Magnified region marked in A. Note the coarse fibre in the middle. C) Facet orientation image representation. Bright areas correspond to angles of approx. 20-26 degrees relative to the paper plane. D) Pore volume image representation. Dark areas correspond to the surface pores detected with a rolling ball. For images B and D the labels are given in μm. The label in C is given in degrees. The surface images shown originate from a heavily calendered non-layered sheet made of a mixture of groundwood (70%) and TMP Rej 30 (30%).

SEM Analysis: Sample Preparation, Image Acquisition and Analysis

Four paper samples of approximately 2x1cm² were cut and embedded in epoxy resin. The preparation, considering embedding, abrading and successive polishing, was performed according to [17]. Thirty SEM cross-sectional images were acquired per series in backscattered mode with 500x magnification in a Hitachi S-3000 variable pressure SEM. The image size was 2560x1980 pixels, having a resolution of 0.1 μm/pixel. ImageJ [16,18] was used for computerized image processing and analysis. The images were automatically thresholded according to [19]. The top and bottom surfaces were defined by a rolling ball having a radius of 15 μm [17,20,21]. Several parameters, such as thickness, porosity, pore height distribution, specific surface area, optical fines content and surface roughness can be derived from the cross-sectional SEM images [21]. A distribution analysis in the z-direction was also performed by dividing the cross-sectional image into 10 equally thick layers. The layer division was based on the top and bottom surfaces as defined by the rolling ball approach (Fig. 2).

Fig. 2: SEM cross-sectional image. A) Image of an uncalendared sample. B) The corresponding binary image. The layers used for distribution analysis have been superimposed in B for clarity purposes. The shown cross-sectional paper structure image originates from a non-layered sheet made of a mixture of TMP Acc 35 (30%) and TMP Rej 80 (70%).
RESULTS and DISCUSSION

Differences between Layered and Non-layered Sheets
Z-directional distributions of the specific surface area of both layered and non-layered sheets made of the same furnish combination are shown in Fig. 3. Contrary to homogeneous sheets, a densification towards the surfaces of the layered sheets is observed. This densification was accompanied by increased specific surface area and optical fines contents in the outermost layers.

Fig. 3: Z-directional distribution (polynomially fitted) of the specific surface area for uncalendered layered sheets (“L” - solid lines and symbols) and non-layered reference sheets (“H” - dashed line and open symbols) of a given furnish combination. The number after the sheet layering mode denotes the minimum and maximum level of the surface layer weight proportion. The examples shown refer to sheets containing TMP reject (TMP Rej 30) in the centre, combined with either TMP Accept (left) or groundwood pulp (right) as second mixture or surface component, respectively.

Figs. 4 and 5 shed some light on the differences between layered and non-layered sheets. The figures depict the paper properties that significantly changed by layered forming, compared to the non-layered reference sheets. The shown relative change of the property refers to the mean value of the property calculated for 12 layered and 12 non-layered sheets, respectively.

The apparent density, thickness and air permeability of the layered sheets were somewhat higher than that of the non-layered sheets, but the difference was not significant. The light scattering coefficient of the uncalendered sheets was significantly improved by 4% upon layered forming, while tensile properties were significantly reduced (between 3% and 17%), Fig 4. These results are in line with earlier findings by Tubek-Lindblom and Salmén [5] and Nesbakk and Helle [6]. Tensile index in MD was more affected than the tensile index in CD. Z-strength was on average 42% lower for layered sheets than non-layered reference sheets.

The bending stiffness was significant improved by 8% upon layering, with stiffness in CD being more affected than stiffness in MD. Paper surface compressibility was found 4% higher for layered and non-layered sheets, when estimated by the PPS method.
Fig. 4: Significant changes in uncalendered laboratory sheet properties as introduced by layered forming.

Significant improvements were found upon layered forming, with respect to the surface microstructure. The mean surface pore volume was close to 20% lower for layered sheets, and steep facets indicating sharp edges of coarse fibres were reduced by 10%, Fig. 5. Also the PPS-roughness showed a significant improvement of the surface quality upon layered forming (13-17%, depending on the calendering level). In accordance with the surface quality improvement was a significant gain in paper gloss by approximately 12%. These results agree with findings of Kinnunen [3] who demonstrated that concentration of fines and fillers through additive layering in the surface layers of SC papers clearly improved surface smoothness and print quality characteristics.

Fig. 5: Significant changes in surface properties of calendered laboratory sheet as introduced by layered forming.

Mechanical Pulp Quality Effects in Layered Sheets

Sheet structure and light scattering
Air permeability was dramatically affected by the pulp type, being 60% lower for TMP accept than groundwood pulp in the paper surface, and 56% lower for TMP Rej 30 than TMP Rej 80 (not shown). The quantitative effect of the pulp quality on air permeability of layered was somewhat lower than indicated by their pure pulp sheets.
Significant differences, with respect to centre layer pulp quality and proportion, were found for the apparent sheet density. The less developed centre pulp (TMP Rej 80) reduced the sheet density by 50 kg/m² on average, and increased the total specific surface area (SSA) significantly by 5%, compared to the highly developed centre pulp (TMP Rej 30), Fig 5. This value corresponds to the SSA difference of pure centre pulp sheets. Also the layer weight proportions and synergy effects between the amount of the surface layer and its quality, as well as the quality of centre and surface pulps, were found to influence the specific surface area significantly. For example, a benefit of the TMP accept compared to groundwood in the paper surface was not apparent at the lowest weight proportion of the surface layer (30% of the total basis weight), but significant at high surface share (70% of the total basis weight). Differences in mean pore height were significant for pure surface or centre pulp sheets, respectively. Even though the mean pore height of the layered sheets was found to increase with a coarser centre layer pulp (TMP Rej 80 vs. TMP Rej 30), the effect was not statistically significant.

The light scattering ability of the layered sheets was significantly affected by the type of centre pulp, Fig. 5 (right). The less developed centre TMP reject resulted in 2.5 units higher light scattering on average, compared to the highly developed TMP reject, which was also the scattering difference between the centre pulps in pure reference sheets. TMP accept gave somewhat higher light scattering coefficients than the groundwood pulp, but the effect was not statistically significant, Fig. 5.

The two surface pulps had approximately equal fines content, but diverging fibre and middle fraction content, mean fibre wall thickness and degree of splitting, Table 2. Reme and Helle [22] modeled the effect of the degree of fibre splitting on the light scattering coefficient based on testing of fibre and handsheet properties of various mechanical pulps. They found the modeled effect of fibre splitting, at constant fibre wall thickness, surprisingly high, with an increase in scattering by 7 units, when the degree of fibre splitting was increased from about 5 to 20%. At the same time was a decrease in mean fibre wall thickness by 0.5 µm modeled to improve light scattering by about 2 units. Thus, considering only the properties of the fibre fractions, it could be expected that the positive effects of high fibre splitting would dominate over the negative effect of high fibre wall thickness on light scattering, and that the groundwood pulp would exceed the TMP accept with respect to light scattering. This was true, as the DSF- sheets made of pure groundwood pulp had 6 units higher scattering than the TMP accept sheet. However, this benefit was not at all exploited in layered sheets, as Fig. 5 shows. This can be explained by pulp quality interactions. Contrary to the TMP accept did the groundwood pulp “loose” much of its scattering potential when combined with the well developed TMP reject (TMP Rej 30), instead of the less developed centre pulp TMP Rej 80.

Fig. 5: Mean effects of layer weight proportions, surface and centre pulp quality on the total specific surface area (left) and the light scattering coefficient (right) of uncalendered layered laboratory sheets.

Also the relative proportions of surface and centre layer pulps were significantly influencing the light scattering, Fig. 5. The total difference in light scattering was six units between the sheets with low surface pulp share (15/70/15) and the sheets with high surface pulp proportion (35/30/35).
Surface smoothness and gloss

Fig. 6 shows the mean effects of layer proportions and layer mechanical pulp quality on the paper surface roughness, as determined by PPS and Laser profilometry. Both methods revealed a significant effect of both the surface and the centre layer pulp quality on the paper surface structure.

Unexpected, the highly split fibres of the groundwood pulp (70%) resulted in rougher surfaces than the relatively less split TMP accept, (30% splitting), Fig. 6. Reme and Helle [22] could show through statistical modeling that a high degree of fibre splitting was beneficial for the smoothness of mechanical pulp handsheets. However, the groundwood pulp also contained 2.1% of coarse fibres (fraction R14), while the TMP screen accept was nearly free of such fibres. The intact fibres in the groundwood pulp had significantly thicker walls than the TMP accept. It can be concluded that the high degree of splitting and a high proportion of middle fraction present in the groundwood pulp, could not compensate for the negative effects of the coarse fibres in this pulp. These findings underline the harmfulness of even small proportions of thickwalled fibres in the sheet surface.

Contradictorily, a lower PPS-roughness was found for layered sheets with the coarse underlying pulp structure (TMP Rej 80), compared to sheets with well developed centre pulp (TMP Rej 30). It is probably due to the measurement principle of the PPS instrument. The applied pressure may have resulted in higher compression of the bulkier centre pulp (TMP Rej 80) than the better consolidated centre layer of the sheets containing TMP Rej 30. This has likely allowed for a closer contact between the paper surface and the measuring head, thus yielding lower roughness readings under pressure. Provatas and Uesaka [23] modeled the paper-press interaction. The authors found that a small fraction of coarse, stiff fibers has a great effect on the surface pore formation, and that surface compressibility may be more important than surface roughness to describe the paper-plate contact in gravure printing.

Heavy calendering (225 kN/m) reduced the relative differences between the pulp types. The thickness of surface layer – as controlled by the weight proportions of surface and centre layer of the sheet - had no influence on either the surface roughness or gloss. This underlines the significance of the quality of the centre layer pulps for the surface smoothness, irrespective of the thickness of the covering surface layer used in this laboratory study. However, keep in mind that the forming and drainage strategy used in commercial papermaking may affect the consolidation of surface and centre pulps differently, compared to laboratory trials.

The paper gloss was found significantly improved by TMP accept in the paper surface compared to groundwood, and significantly reduced by a less developed centre pulp (TMP Rej 80), compared to TMP Rej 30, Fig. 7(right). Fig. 7 (right) shows that the microsurface roughness, expressed by mean facet orientation angle, correlated well with the paper gloss of the layered sheets. Similar correlations have been reported for commercial SC-paper, though at higher gloss levels [14, 15, 20]. The roughness and gloss-values determined for calendered DSF-sheets made of the two surface pulps are given as reference. Again the advantage of the TMP screen accept versus the groundwood pulp in terms of the surface quality in layered sheets is obvious. The finding that differences in gloss and surface smoothness were significant between layered sheets with either TMP accept or groundwood in the surfaces, but marginal and not significant for one-layered sheets made of these two pulps, can be explained by positive synergy.
effects of centre and surface pulp quality. For example, the gloss level of highly calendered sheets containing TMP accept combined with TMP Rej 80 was 1.5 units higher than for sheets combining groundwood and TMP Rej 80. Replacing TMP Rej 80 with the well developed centre layer pulp TMP Rej 30 increased the gloss for both surface pulps, but the gain was much greater for TMP Acc 35. The gloss difference increased to 2.1 units.

![Graph showing gloss levels for different pulp combinations.](image)

**Fig. 7:** Mean effects of layer weight proportions, surface and centre pulp quality on the gloss of calendered layered laboratory sheets (left). Correlation between surface micro-structure, expressed as mean facet orientation angle, and paper gloss for calendered layered laboratory sheets (right).

**Tensile index and z-strength**

The higher bonding potential of the TMP accept surface pulp, as found for the one-layered reference sheet (10 units higher tensile index compared to GW 35), was also proving significant in layered sheets (7 units higher on average), Fig. 8. TEA was 31% higher and rupture stretch was 10% higher for the sheets with TMP accept in the surface, compared to the groundwood reference. The difference in centre pulp bonding ability had a major effect on the in-plane and out-of-plane strength properties of layered sheets, as expected. Tensile strength was 31% lower for the sheets with less developed centre pulp, and z-strength was even 46% lower, compared to the well developed refined TMP reject in the central sheet layer. Respective differences in pure parent pulp sheets were much lower, 15% and 7%, respectively. The weight split between surface and centre layer pulps was not significant for the strength of the DSF-sheets, Fig 8.

![Graph showing tensile index and z-strength for different pulp combinations.](image)

**Fig. 8:** Mean effects of layer weight proportions, surface and centre pulp quality on the tensile index (left) and the z-directional strength (right) of uncalendered layered laboratory sheets.

**Bending stiffness and compressibility**

Bending stiffness and paper compressibility benefited both strongly from placing the less developed reject pulp in the centre, Fig. 9. The stiffness difference brought about by centre layer pulp variation was 24%, while compressibility at 4 MPa load varied by 8.5%. In pure centre pulp sheets, the bending stiffness differed by only
10%. The effect of the paper surface pulp quality was opposite, but significant for stiffness and compressibility. The TMP accept pulp increased the stiffness compared to the groundwood pulp, likely due to a higher E-modulus. The more particulate groundwood pulp facilitated higher paper surface compressibility than the significantly finer and more collapsible fibres of the TMP accept, Fig. 9. However, the quality of the surface pulp was only significant for compression loads up to 6 MPa. Paper compressibility was also significantly influenced by the interactions between the respective layer weight proportion and layer pulp quality.

![Significance (95% confidence level)](image)

**Fig. 9:** Mean effects of layer weight proportions, surface and centre pulp quality on the bending stiffness (left) and the paper compressibility (right) of uncalendered layered laboratory sheets.

**CONCLUSIONS**

Results of this laboratory study verify the potential of layered forming for the improvement of critical properties of wood-containing high-quality printing papers, such as surface smoothness, paper gloss, light scattering and bendability. The significant increase in printability was accompanied though by a reduction in bonding-sensitive properties, such as tensile index, rupture elongation, TEA and especially z-directional strength. Addition and controlled layering of bonding active fines and/or dry-bond agents are measures supposed to compensate for the strength reduction, but these have not been investigated in this study.

The positive impact of layered forming on for example surface properties may even be enhanced by exploiting synergistic effects from optimal combinations of centre and surface layer pulp qualities. However, the performance of a given pulp in layered sheets does not necessarily need to correspond to its quality potential estimated from a conventional one-layer laboratory reference sheet. Thus pulp quality effects may be enhanced or become apparent, due to lower relative basis weight of the components in layered sheets. This was demonstrated for the initially high light scattering potential of the groundwood surface pulp, which was not exploited in layered sheets. Another example relates to the significant differences in smoothness and paper gloss of layered sheets with surfaces made of either groundwood or TMP accept, which were not at all predictable from the reference sheet surface characteristics of these pulps.

Advanced high-resolution laser profilometry and microscopic techniques combined with automatic image analysis have been applied to successfully distinguish and quantify relevant characteristics of the paper surface and z-directional structure, which were not accessible by conventional paper testing. Findings of this study have underlined the importance and necessity to improve our understanding of pulp and furnish interactions, in order to optimise both furnish composition and sheet structure for a given product. Interactions within more complex furnishes, consisting of different pulp types organised in layered sheets, will be the topic of an upcoming study at PFI.

**ACKNOWLEDGEMENTS**

Norske Skog ASA and the Research Council of Norway are acknowledged for financial funding. Personnel from Norske Skog Research and Development and Saugbrugs laboratories are thanked for providing pulps, and
performing calendering trials. Many thanks go to Merete Wiig, Berit Leinsvang, Ida Christiansen, Kristin Stensønes, Mirjana Filipovic, Kenneth Aasarod, Eirik Thorgaard and Per Olav Johnsen from PFI for their efforts in the laboratories and at the microscope.

REFERENCES


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Outline

• Background and objective
• Strategy and experimental
• Differences between layered and non-layered sheets
• Mechanical pulp quality effects in layered sheets
• Conclusions
Why investigate multilayering for printing papers?

• Increasing demands on printability
  • surface smoothness, gloss, opacity, compressibility
• Maintain strength, stiffness, dimensional stability
• Layered forming established for many paper and board grades
• Challenge for layered wood-containing printing papers:
  ➔ find optimal balance between runnability and printability demands through
    • suitable layered structure
    • optimal furnish composition
Main objective

Establish principal knowledge as to what extent and in which direction relevant paper properties change, depending on the mechanical pulp quality in different sheet layers.
Strategy

- Layered and non-layered laboratory sheets (DSF) made of well characterised mechanical pulps
- Significant differences in layer pulp quality to assure statistically significant results
- Statistical methods for experiment design and evaluation
- Standard and advanced testing methods for relevant sheet properties
### Factorial design

<table>
<thead>
<tr>
<th>Surface pulp quality</th>
<th>Centre pulp quality</th>
<th>Layers</th>
<th>Layer weight proportions surface / centre / surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMP screen accept (TMP Acc 35)</td>
<td>TMP refined screen reject (TMP Rej 80)</td>
<td>Non-layered</td>
<td>15%/70%/15%</td>
</tr>
<tr>
<td>Low fibre splitting</td>
<td>Less developed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwood (GW 35)</td>
<td>TMP refined screen reject (TMP Rej 30)</td>
<td>Three-layered</td>
<td>25%/50%/25%</td>
</tr>
<tr>
<td>High fibre splitting</td>
<td>Well developed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>÷</td>
<td>÷</td>
<td>÷</td>
<td>35%/30%/35%</td>
</tr>
</tbody>
</table>
Layered and non-layered sheets quality range

- **A-series:** TMP Acc 35 + TMP Rej 80
- **B-series:** TMP Acc 35 + TMP Rej 30
- **D-series:** GW 35 + TMP Rej 80
- **E-series:** GW 35 + TMP Rej 30

**Tensile index, kN/m:**
30 35 40 45 50 55 60 65 70

**Light scattering coefficient, m²/kg:**
30 35 40 45 50 55 60 65 70 80
Principal differences between layered and non-layered sheets

Desired U-shaped structure achieved.
Significant differences between layered and non-layered sheets

Thickess and air permeability higher for layered sheets, density lower, difference not significant.
Significant differences between layered and non-layered sheets

Relative property change introduced by layering (%), calendered sheets

- Surface pore volume
- Surface facet orientation
- Surface roughness Rq
- PPS roughness 1MPa
- Hunter gloss
Effects of layer pulp quality on light scattering coefficient

- Effects of surface pulp quality differences much lower than expected.
- Effects of centre pulp quality differences as expected.
- Negative synergy between GW 35 and TMP Rej 30.
Effects of layer pulp quality on surface smoothness

- Surface pore volume (75 kN/m)
  - Centre pulp quality: Surface pulp quality: Layer proportions
  - TMP Rej 80: TMP Rej 30: TMP Acc 35
  - GW 35: 35/30/35: 25/50/25: 15/70/15

Significance (95% confidence level)
- No
- Yes
- Yes

Surface pore volume (75 kN/m)

Layer proportions: GW 35: TMP Acc 35: TMP Rej 30: TMP Rej 80

No significance

Yes significance
Effects of layer pulp quality on paper gloss

Significant effect of both surface and centre pulp quality.
Effects of layer pulp quality on tensile strength

- Effects of surface pulp quality differences lower than expected.
- Effects of centre pulp quality differences much stronger than expected.
Effects of layer pulp quality on z-strength

Effects of centre pulp quality differences strongly emphasized:

7% difference in non-layered vs. 46% difference in layered sheets.
Effects of layer pulp quality on bending stiffness

- Effects of surface pulp quality differences stronger than expected.
- Effects of centre pulp quality differences much stronger than expected.
Effects of layer pulp quality on paper compressibility

Effects of surface pulp quality differences smaller than expected.

Effects of centre pulp quality differences stronger than expected.
Conclusions

• Results of this laboratory study verify the potential of layered forming for the improvement of critical properties of wood-containing high-quality printing papers, such as surface smoothness, paper gloss, light scattering and bendability.

• The significant improvement in printability was accompanied by a reduction in bonding-sensitive properties, such as tensile index, rupture elongation, TEA and especially z-directional strength.

• Positive effects of layered forming e.g. on surface properties may be enhanced by exploiting synergistic effects from optimal combinations of centre and surface layer pulp qualities.
Conclusions cont´d

• This study has indicated how and to what extent different paper properties of layered sheets can be influenced by the choice of mechanical pulp quality.

• The performance of a given pulp in layered sheets does not necessarily need to correspond to its quality potential estimated from a conventional one-layer laboratory reference sheet.

• Thus pulp quality effects may be enhanced, decreased or become apparent, due to interaction effects and relatively lower basis weight of the components in layered sheets.
Conclusions cont´d

- E.g. the initially high light scattering potential of the groundwood surface pulp was not exploited in layered sheets.

- Significant differences in smoothness and paper gloss of layered sheets with different surfaces pulps were not at all predictable from the reference sheet surface characteristics of these pulps.

- Strength properties benefited greatly from a well developed centre pulp while the opposite was true for stiffness and compressibility.
Acknowledgements

• Norske Skog ASA and the Research Council of Norway

• Merete Wiig, Ida Kristiansen, Berit Leinsvang, Mirjana Filipovic, Kristin Stensønes, Kenneth Aasarød, Eirik Thorgaard and Per Olav Johnsen (PFI)

• Personnel from Norske Skog Research & Development and Norske Skog Saugbrugs Mill