

Influence of calendering conditions on paper surface characteristics—a comparison between hard-nip, soft-nip, and extended soft-nip calendering

ISABEL ENDRES AND GUNNAR ENGSTRÖM

ABSTRACT: This study investigated the influence of different calendering conditions on newsprint surface and absorption characteristics, strength, and compression uniformity. We used a combination of traditional and new measurement techniques to evaluate newsprint calendered using a hard-nip, a conventional soft-nip, and an extended soft-nip. This study points out and compares the advantages and disadvantages of the respective calendering techniques.

In all cases, flocs carried the greater part of the load. The different calendering techniques yielded dissimilar compression patterns. At constant process parameters, flocs were flattened most in hard-nip calendering, which had a positive effect on smoothness, gloss, thickness uniformity, and ink hold out. However, it negatively affected tensile strength, gloss uniformity, and print mottle. Extended soft-nip calendering produced opposite effects, including a rougher surface, non-uniform thickness, and less print mottle.

Application: A combination of traditional and new measurement techniques to analyze the effects of calendering on paper properties is introduced.

Calendering is performed mainly to enhance paper surface characteristics, such as gloss and smoothness, and thereby create a higher quality print substrate. However, different printing techniques require different paper characteristics. In rotogravure, good contact between the paper and the printing cylinder is crucial to a good print result. Consequently smoothness and compressibility are important. Other printing techniques, such as offset, have a low demand on smoothness, but a considerably higher demand on uniformity of density and porosity distribution. Therefore paper is calendered differently, depending on the printing process to be used.

In general, achieving a uniform calendering treatment is rather difficult considering the non-uniform mass distribution of the paper. This non-uniformity shows in an uneven thickness profile of the uncalendered paper, with flocs giving areas of higher mass and intermediate areas of lower mass [1]. With a hard-nip, a fairly uniform thickness is obtained by compressing fiber flocs substantially more than valleys, which remain almost uncompressed [2-4]. High smoothness and gloss are achieved. However, the density disparity from a fiber floc to a valley in the paper can diminish end-product quality with respect to gloss and print mottle.

In a conventional soft-nip, on the other hand, the load is distributed over a larger area due to the deformable polymer roll cover. The paper is thus exposed to lower pressure levels for a slightly longer time. The porosity and density distributions are more uniform, but flocs show in the form of thickness variations [5].

In an extended soft-nip, the load is distributed over an even larger area. The pressure is assumed to be less concentrated on the thicker areas in the paper (fiber flocs) than in conventional calendering, and density variations are further reduced [6].

To fully understand the interplay between calendering conditions and paper properties and their influence on print quality, local stochastic properties of the paper need to be further characterized [7].

In this study, traditional and modern measurement methods are applied to characterize differences between the calendered papers. A combination of two new methods for characterizing local surface characteristics is introduced. We measured the surface topography using OptiTopo [8], and the compression uniformity was determined using a local contact and stress analyzer (LCSA) [9]. In

height maps of the hard-nip and soft-nip calendered papers, we detected flattened areas of the size of fiber flocs. On the extended soft-nip calendered paper, the flattening was much less intense. In the LCSA, the local pressure distribution on the calendered paper surfaces was measured under low applied pressure to preserve the calendering effect. We found that on all the calendered papers, flocs carried the greater part of the load. The structure of these load-carrying flocs changed significantly depending on the calendering conditions. At constant process parameters, flocs were flattened most in hard-nip calendering, which had positive effects on smoothness, gloss, thickness uniformity, and ink hold out. Nevertheless, it negatively affected tensile strength, gloss uniformity, and print mottle. Extended soft-nip calendering produced a rougher surface and a non-uniform thickness, but less print mottle.

CALENDERING

Newsprint (50 g/m², 65% thermomechanical pulp [TMP], 35% recycled) was calendered in the STFI pilot calender using a hard-nip, a conventional soft-nip and an extended soft-nip at various line loads, speeds, and temperatures. The calendering conditions are summarized in **Table I**.

CALENDERING

Calendering mode	Line Load, kN/m		Machine Speed, m/min		Temp. °C	
Hard-nip						
Soft-nip	70	210	500	1000	80	120
Extended soft-nip						

I. Calendering conditions.

	Hard-nip	Soft-nip	Extended soft-nip
Thickness reduction, %	28.3	22.5	12.7
Gloss increase, %	100.2	70.4	53.0

II. Influence of calendering techniques on thickness and gloss.

	Nip Load, kN/m		Machine Speed, m/min		Temp. °C	
	70	210	500	1000	80	120
Thickness reduction, %	16.5	22.6	19.1	19.2	19.0	20.6
Gloss increase, %	30.9	101.2	65.8	61.9	56.5	83.9

III. Influence of process parameters on thickness and gloss.

The extended nip used a rubber belt (Sh° A 87). The polymer roll in the soft-nip had a hardness of Sh° D 91. In all the trials the paper passed the calender nip once.

CHARACTERIZATION METHODS

Paper properties were determined using standard methods and internal STFI test methods. Paper gloss was measured using ISO 8254-1:1999. Paper thickness was measured using an STFI-method described by Fellers et al. [10]. The tensile strength index was determined in machine direction and averaged over 10 single measurements per sample. The topography was measured using OptiTopo, a photometric stereo imaging method [8]. Height maps (10 mm x 10 mm) and height distributions were calculated, indicating both positive and negative deviations from the average height.

The compression uniformity was characterized using the LCSA method [9], which uses a high-resolution pressure-sensitive film in a platen press and image analysis to calculate the pressure distribution on the paper surface (Fig. 1).

In this method, a sample is compressed under a given force between a smooth plate and a pressure-sensitive film which is positioned on a glass plate. The area of interest is lit from below with annular illumination. The force is increased and then held constant for 30 seconds, and an image of the grey-level changes on the pressure-sensitive film is collected with a CCD-camera. Via a calibration function, the grey-level image is translated into a pressure map, in which each pixel represents the local pressure value on the sample.

The image size for this investigation was 12.6 mm x 9.5 mm with a spatial resolution of 12.3 µm. The average applied pressure was 4 MPa. The water absorption was measured using the Bristow wheel [11].

We printed a selection of samples with Sun Chemical black newsprint offset printing ink using a Pruefbau laboratory printing press (Peissenberg, Germany), at a machine speed of 1 m/s and a force of 800 N. The printed samples were left to dry for 24 hours at 23°C and 50% relative humidity. The print density was thereafter determined using a color densitometer. This device measures color density as the logarithm to the base 10 of the ratio of the reflectivity of the paper to the reflectance factor of the printed surface of the paper. The print mottle was measured on printed sheets with a color density of 1.3. We evaluated an area of 6 x (21.7 x 21.7 mm²) per sample. The printed samples were scanned in a flat bed scanner and the coefficient of variation in reflectance on the printed sheets was measured in several wavelength bands.

RESULTS

Influence on thickness and gloss

Paper calendered in a hard-nip was compressed most and developed the highest gloss, whereas the extended soft-nip calendered paper was compressed least and gave the lowest gloss (Table II).

With respect to process parameters (Table III), the thickness was reduced most with increasing nip load, and the gloss increased with both increasing nip load and increasing temperature. The machine speed (or dwell time) had no effect on either thickness or gloss [see 12-14].

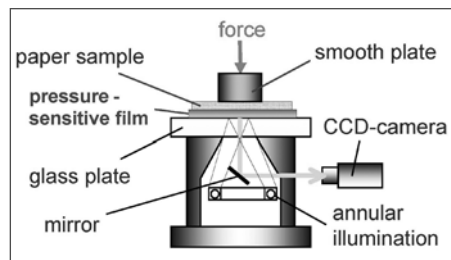
Tensile strength as affected by calendering

Figure 2 compares the tensile strength index for the uncalendered and the calendered sheets at constant calendering process parameters. The tensile strength was lowered most by hard-nip calendering, in which the paper was exposed to the highest compressive forces. Both soft and extended soft-nip calendering decreased the tensile strength comparatively less.

Influence on water absorption, ink absorption, and print mottle

The compression-related absorption behavior was compared at constant process parameters (as in Fig. 2). Figure 3 shows the water absorption as measured with the Bristow wheel, where the transferred water is plotted as a function of time. At short absorption times, the water transfer to the uncalendered paper was lower compared to that of the calendered papers. No significant difference in water absorption could be detected between the calendered papers.

Figure 4 shows a measure for the ink absorption, where the ink amount required to produce a print density of 1.3 is plotted as a function of calendering technique. Unlike the water absorption measurements, clear differences between the calendered papers were observed. While the uncalendered paper required the highest amount of ink to reach the target print density, all calendered papers decreased the ink demand. The extended soft-nip calendered paper required the comparatively highest amount of ink, whereas the hard-nip calendered paper required considerably less ink. This may be explained by the level of densification. As could be seen in Table I, the thickness was decreased most in the hard-nip and thus the sheet was densified most. Leaving the dominant role of fiber swelling, as in the case of water absorption aside, it seems logical that an oil-based ink absorbs less easily into a denser paper, with presumably less



1. Experimental set-up of the local contact and stress analyzer.

pore volume than into a bulkier structure.

A measure for the print mottle is given by the coefficient of variation in reflectance, which is here presented as a function of wavelength bands. The hard-nip calendered sheet produced the highest print mottle and the extended soft-nip the lowest (Fig. 5).

Influence on the surface topography

Topographical data for the differently calendered papers are presented in height maps, in which grey-scale coding indicates height variations in micrometers.

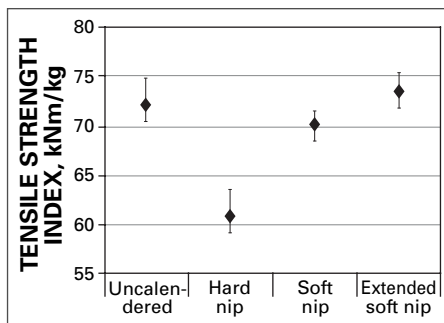
Figure 6 shows typical examples for the uncalendered, hard-nip, soft-nip, and extended soft-nip calendered paper. Figure 7 gives the corresponding height distribution curves.

The uncalendered paper had the least uniform surface topography, followed by the extended soft-nip and the soft-nip calendered papers. The smoothest surface was produced by hard-nip calendering. On both the hard-nip and the soft-nip calendered papers, flattened areas of the size of flocs were detected.

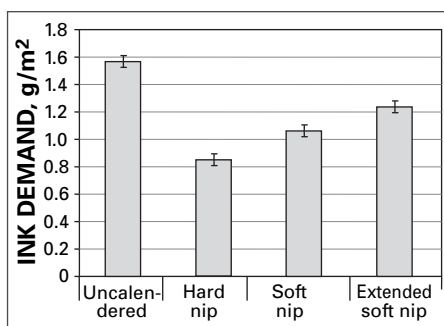
A frequency analysis of the surface topography (Fig. 8) indicated that all the calendering techniques reduced the standard deviation in the 0.5 mm to 4.0 mm wavelength bands. The reduction was greatest for the hard-nip calendered paper and least for the extended soft-nip calendered paper. This is most likely linked to the compression and associated with the flattening of fiber flocs. Height variations in other wavelength bands were unaffected by the calendering.

Compression uniformity

We have used pressure maps to describe the effects of calendering on the paper surface. The different calendering techniques yielded very dissimilar compression patterns, as shown in Fig. 8. In all cases, fiber flocs carried the greater part of the load. The structure of these load-carrying flocs was, however, changed sig-



2. Tensile strength index as a function of calendering technique. Process parameters in calendering: nip load = 210 kN/m; machine speed = 500 m/min; temperature = 120°C.



4. Ink demand to reach a print density of 1.3 as a function of calendering technique. Process parameters in calendering: nip load = 210 kN/m; machine speed = 500 m/min; temperature = 120°C.

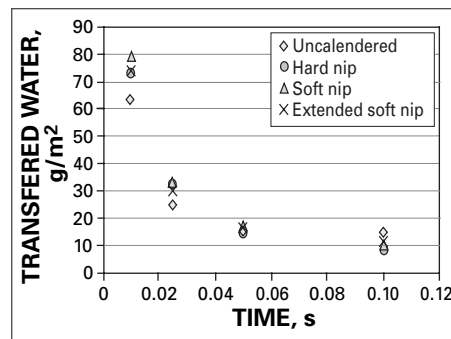
nificantly, depending on the calendering conditions.

In the pressure map for the uncalendered paper (Fig. 9a), a small-scale floc structure (1-2 mm) can be seen. Pressure peaks are spread out to numerous fibers and fiber crossings.

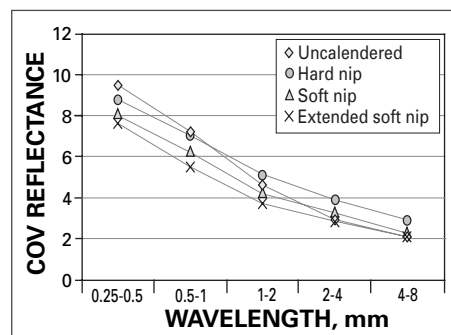
On the hard-nip calendered paper (Fig. 9b), the load was spread fairly uniformly over larger areas (here approximately 4-8 mm). These areas are presumably fiber flocs which have been deformed during calendering to such an extent that they form a rather uniform surface under compression.

On the soft-nip calendered paper (Fig. 9c), the load was spread over larger areas (flattened flocs), similar to those seen on the hard-nip calendered paper. However, on these flattened flocs, the load was spread less uniformly and floc tops were exposed to pressure peaks.

On the extended soft-nip calendered paper (Fig. 9d), the greater part of the surface was exposed to very low local



3. Water absorption as measured with the Bristow wheel, characterized by the quantity of water transferred to the paper sample as a function of time. Process parameters in calendering: nip load = 210 kN/m; machine speed = 500 m/min; temperature = 120°C.

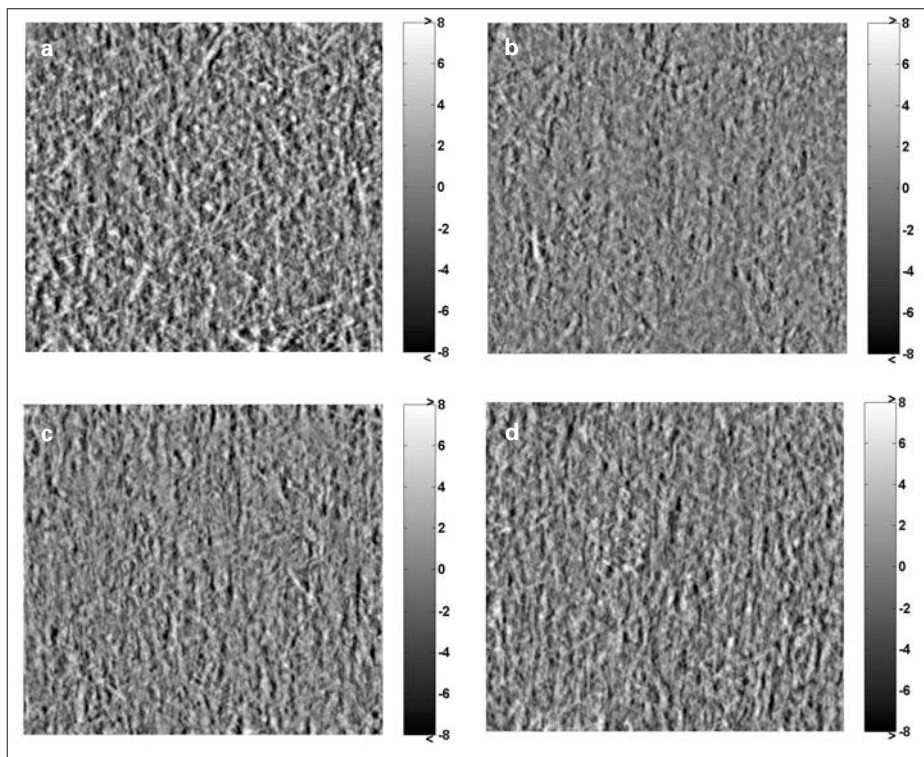


5. Coefficient of variation in reflectance as a function of wavelength bands. Process parameters in calendering: nip load = 210 kN/m; machine speed = 500 m/min; temperature = 120°C.

pressures, whereas floc tops experienced exceedingly high local pressures. These peaks could reach up to 40 MPa on the conventional and extended soft-nip calendered paper. The pressure distribution on the hard-nip calendered paper showed a much lower maximum pressure (~25 MPa), due to the smoothening by extensive compression during the calendering. Figure 10 presents the data for the pressure maps of Fig. 8 in a pressure distribution graph.

Figure 11 shows the standard deviation in pressure for different wavelength bands. The extended soft-nip calendered paper exhibited the highest overall standard deviation and the hard-nip calendered paper the lowest. The peak in the two lowest bands originated from load-carrying fiber crossings that were exposed to higher pressures than their surroundings.

CALENDERING



6. Height maps calculated from OptiTopo measurements on uncalendered and calendered newsprint (50 g/m²). Process parameters in calendering: nip load = 210 kN/m; machine speed = 500 m/min; temperature = 120°C. Grey-scale bar in micrometers. Image size = 10 mm x 10 mm. (a) Uncalendered; (b) Hard-nip calendered; (c) Soft-nip calendered; (d) Extended soft-nip calendered.

We determined the influence of line load, machine speed, and temperature on compression uniformity. For all calendering techniques, the compression uniformity increased with both increasing nip load and increasing machine speed (shorter dwell time). Temperature had only a minor effect on the uniformity of the pressure distribution.

DISCUSSION

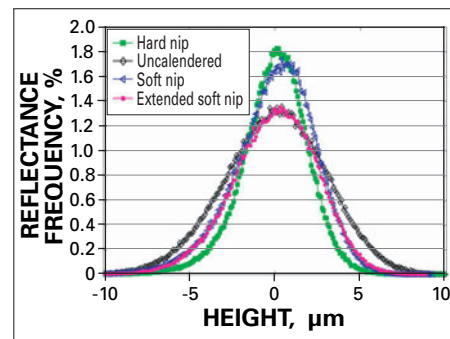
For this study, we measured thickness, gloss, tensile strength, absorption, print mottle, surface topography, and compression uniformity on calendered newsprint papers. Trends are summarized for the two extreme cases of hard and extended soft-nip calendering, which were compared at constant process parameters in Table IV. The plus and minus signs are to be interpreted as high and low values of the respective measured property. Soft-nip calendering produced results that ranked between hard and extended soft-nip calendering.

In summary, paper calendered in a hard-nip was compressed most and it developed the highest gloss (and the highest gloss variations, visually

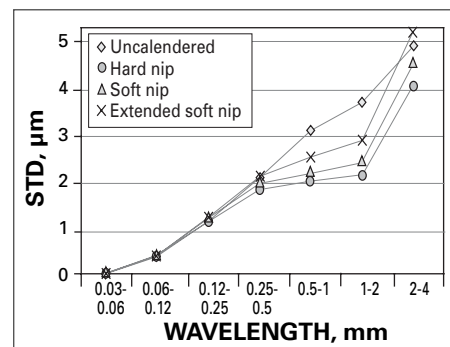
assessed). In the height map (Fig. 6b), large patches of flattened, smooth surfaces were seen. In the pressure map (Fig. 9b), areas of the same order of magnitude carried a very uniformly distributed load. These smooth, load-carrying and glossy areas on the surface of the hard-nip calendered paper represent flattened flocs.

These findings are in agreement with the theory that fiber flocs are exposed to much higher compressive stresses than valleys during hard-nip calendering. As a consequence, flocs are compressed considerably more, developing a smoother surface, higher gloss, good ink hold out, and a uniform thickness profile. However, the greater the disparity between flocs and valleys, the less uniform is the gloss and the ink absorption, which can result in mottling. Another drawback that is linked to a higher densification level is the lowered tensile strength, which can cause runnability problems.

Thickness reduction and gloss increase were slightly less in the soft-nip calendered paper than in the hard-nip calendered paper. However, smoothened



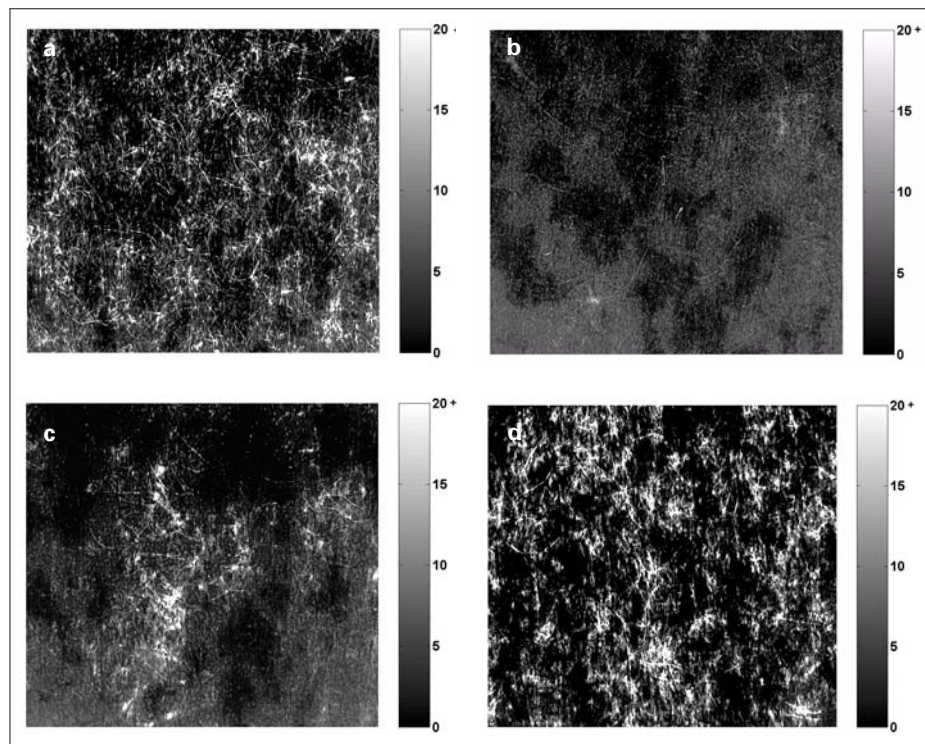
7. Height distributions corresponding to height maps in Fig. 2.



8 Height standard deviation in wavelength bands.

patches could still be seen in the height map (Fig. 9c). The pressure distribution on the flattened flocs was more non-uniform than in the hard-nip calendered paper. This indicates that the pressure distribution during the soft-nip calendering was more uniform than that in a hard-nip, with the flocs being compressed less and the thickness non-uniformity being less affected.

On the extended soft-nip calendered paper, the thickness reduction and gloss increase were the least. The height map showed no patches of smooth areas and the pressure maps indicated that the load was spread very uniformly over the paper surface, creating peaks only on floc tops. The lower densification level in this calendering technique led to a comparatively lower ink hold out, but less print mottle. The latter may be explained by the fact that flocs and valleys were exposed to approximately the same compressive stresses in the nip. Differences between compressed flocs and uncompressed valleys, as seen in both the conventional calendering techniques, are nearly non-existent, as the polymer belt in the extended soft-nip followed the contour of the paper to a much higher extent.



9. Pressure maps of newsprint (50 g/m²) calendered with different calendering techniques. Process parameters in calendering: nip load = 210 kN/m; machine speed = 500 m/min; temperature = 120°C. Images taken with LCSA after calendering. Mean applied pressure = 4 MPa; grey-scale bar in MPa. Image size = 12.6 mm x 9.5 mm. (a) Uncalendered; (b) Hard-nip calendered; (c) Soft-nip calendered; (d) Extended soft-nip calendered.

Figure 12 summarizes the main findings graphically.

CONCLUSION

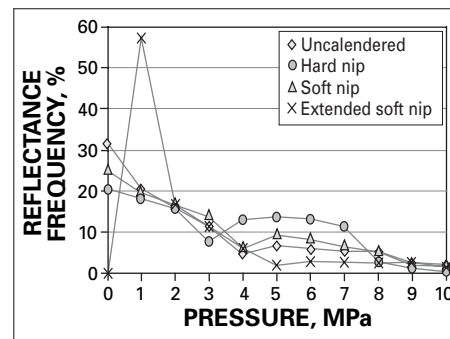
Hard-nip calendering is the technique of choice when the demands on smoothness and thickness uniformity are high, such as in rotogravure printing. It also produces a high ink hold out, which is of interest in offset printing. Drawbacks include the lower tensile strength and possible runnability problems. In addition, the risk of mottling due to differential compression of flocs and valleys is heightened. Extended soft-nip calendering, which represents the other extreme, produces a rougher surface, which is less suitable for rotogravure printing. The gloss and print mottle are, however, much lower, which are beneficial for offset and flexographic printing. The bulk of the paper and the tensile strength are preserved, whereas gloss and ink hold out are comparatively lower. The way of compromise leads to soft-nip calendering, which gives results that rank between the two extremes of hard-nip and extended soft-nip calendering. **TJ**

ACKNOWLEDGEMENTS

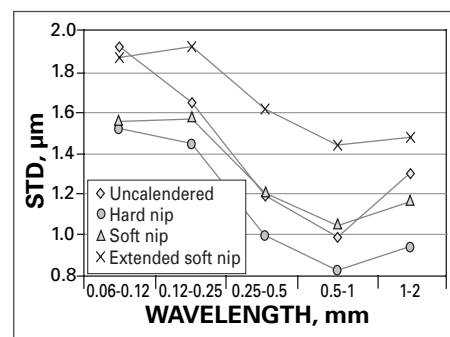
The authors thank M. Bouveng for carrying out the water absorption test. We also greatly acknowledge the Swedish Forest Industries Research Foundation, the Knowledge Foundation, and VINNOVA (Swedish Agency for Innovation Systems). Associate professor J.A. Bristow assisted with the linguistic revision of the manuscript.

LITERATURE CITED

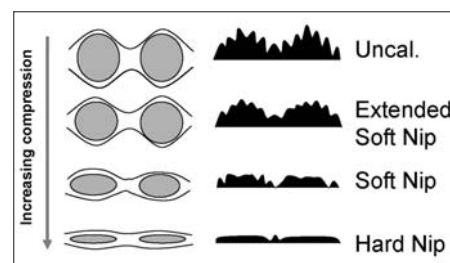
1. Crotagino, R.H. and Gratton, M.F., *Pulp Paper Can.* 88(12): T461(1987).
2. Retulainen, E., Moss, P., and Nieminen, K., *J. Pulp Paper Sci.* 23(1): 34(1997).
3. Steffner, O., Nylund, T., and Rigdahl, M., *Nordic Pulp Paper Res. J.* 13(1): 68(1998).
4. Rättö, P., Hornatowska, J., and Rigdahl, M., *Nordic Pulp Paper Res. J.* 16(3): 172(2001).
5. Kajanto, I.M., *Tappi 1991 Paper Physics Conference Proceedings, TAPPI PRESS, Atlanta, Georgia, USA, p. 281.*
6. Wikström, M., Nylund, T., and Rigdahl, M., *Nordic Pulp Paper Res. J.* 4(12): 289(1997).



10. Pressure distributions corresponding to pressure maps in Fig. 5.



11. Standard deviation in pressure as a function of wavelength bands.



12. Schematic sketch of the effect of different calendering techniques on the paper structure. Compression of flocs (left); surface topography (right).

	Hard-nip	Extended soft-nip
Gloss	+	-
Thickness reduction	+	-
Surface roughness	-	+
Floc flattening	+	-
Tensile strength index	-	+
Ink hold out	+	-
Print mottle	+	-

IV. Comparison of measured characteristics for hard-nip and extended-soft-nip calendered sheets.

7. Provatas, N. and Uesaka, T., *J. Pulp Paper Sci.* 29(10): 332(2003).
8. Hansson P. and Johansson P.-Å., *Nordic Pulp Paper Res. J.* 14(4): 314(1999).

9. Endres, I., Vomhoff, H., and Ström, G., *Tappi 2003 Paper Physics Conference Proceedings*, TAPPI PRESS, Atlanta, p. 229.
10. Fellers, C., Andersson, H., and Hollmark, H., in *Paper Structure and Properties* (J.A. Bristow and P. Kolseth, Eds.) Marcel Dekker Inc., New York, New York, USA, 1986, p. 151.
11. Bristow, J.A., *Svensk Papperstidning* 70(19): 623(1967).
12. Chapman, D.L.T., and Peel, J.D., *Paper Tech.* 10(2): 116(1969).
13. Keller, S.F., *Tappi 1992 Coating Conference Proceedings*, TAPPI PRESS, Atlanta, p.71.
14. Rätto, P. and Rigdahl, M., *Nordic Pulp Paper Res. J.*, 13(3): 180(1998).

Received: March 2, 2005

Revised: July 7, 2005

Accepted: July 28, 2005

This paper is also published on TAPPI's web site <www.tappi.org> and summarized in the September *Solutions! for People, Processes and Paper* magazine (Vol. 88 No. 9).

INSIGHTS FROM THE AUTHORS

Comparisons of different calendering techniques on newsprint are rather rare. This research compares and shows the effect of the calendering treatment on the paper using a combination of unique and conventional test methods.

The development of the Local Contact and Stress Analyzer, including the development of a high-resolution pressure-sensitive film, took its time but has now become a promising and interesting research tool. Compression uniformity is the topic of my PhD project, in which a new method for the local contact characterization was developed.

During the course of the research, the compression uniformity measurements on the differently calendered sheets were most interesting to me. To see how the pressure distributes locally on the calendered sheets

broadened my understanding of how the calendering treatment affects the paper structure.

This paper may be helpful to paper-makers or mill managers choosing which calendering technique to employ when considering newsprint production. As a next step, we will continue looking into compression uniformity and will try to link structural paper properties and their behavior under compression to print quality.

Endres is with STFI-Packforsk/Karlstad University, Box 5604, SE-11486 Stockholm, Sweden; Engström is with Karlstad University, Department for Chemical Engineering, SE-65188 Karlstad, Sweden. Email Endres at isabel.endres@stfi.se.



Endres



Engström