Print Quality of Linerboard in Commercial Water-based Flexography

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Abstract: Seventeen North American linerboards — brown, white-top, and solid bleached kraft — were printed on a commercial web flexo press with water-based inks. Press variables included ink viscosity, plate hardness, and printing pressure. The quality of a halftone photograph increased as the board became smoother and brighter, and also increased with a harder printing plate and a higher viscosity ink. Contrary to conventional wisdom which states that bar codes printed on very dark or rough linerboards are more difficult to read, readability was independent of linerboard brightness and roughness. However, bar code readability was poorer on more water-repellent boards, or with inappropriate printing pressures (whether too high or too low). Across the sample range solid print density and ink holdout decreased as the liners became rougher and more water-repellent. However, within each grade there was no correlation between print density, roughness, and surface chemistry.

INTRODUCTION

Corrugated boxes have long been used for the packaging and protection of various goods. In the past, strength and durability were the major quality considerations. However, during the last two decades, the retail industry has set new demands for corrugated boxes. As more and more goods are left in the shipping boxes and are sold directly from the shelf, high quality graphics are required on the boxes to promote the product within.

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As the demand for better print quality increases, corrugated board producers have recognized that printing of the boxes, once used only for identifying the containers, has become one of the primary challenges in the manufacture of high quality corrugated board [1]. While there are well-accepted tests for measuring the strength properties of linerboard, corrugating medium, and combined board [2], there are currently no commonly-accepted testing methods for printability.

Uncoated linerboard is printed almost exclusively by water-based flexography. Print quality criteria for the flexo printing of linerboard and corrugated board have been reviewed by Zang and Aspler [3]. Although relevant data are relatively sparse, the literature claims that print quality depends largely on dynamic water absorption, surface smoothness, and surface formation (i.e., the mass distribution of fibres at the linerboard surface).

However, some common mill tests for quality control, such as the Cobb water absorption test and air permeability measurements, bear little or no relevance to flexo print quality [3]. On the other hand, some non-standard tests, such as the IGT and Bristow absorbency tests, appear to correlate to a certain degree with flexo print quality. These findings have been explained by assuming that the flexo printability of linerboard is mainly associated with short-time absorption phenomena.

Much remains poorly quantified in our knowledge of how to improve and test for linerboard surface quality. For example, to improve printability of uncoated linerboard, it is unclear whether improving surface smoothness by calendering or reducing water absorbency by sizing is more efficient. Also, as printing speed increases and flexo inks become more viscous, other factors, such as pH, wettability, and surface strength may play an important part in determining flexo printability of the liners.

Bar codes are of vital importance to the customer. Universal Product Codes (UPC) are used for both inventory control and for pricing at the checkout counter. Much of bar code readability belongs to the initial design of the bar code, and so is outside the scope of this work. Carlson [4, 5] and Eldred [6] have reviewed the optical and mechanical requirements for correct bar codes.

Bar code readability depends on the discrimination between the printed bars and the unprinted spaces between the bars. The Uniform Code Council has claimed that any board with a reflectance less than 31.6% (optical density greater than 0.5) is not acceptable [7]. A strict interpretation of this claim would exclude many brown linerboards. The saving grace is in the print contrast, or the difference between the optical density of the ink and that of the board. A higher print density can, in part, compensate for the darker colour of the unprinted board. According to an ANSI standard [8], edge sharpness and the number of defects are also important.

In addition to the optical properties of the substrate, we must also consider the physical properties of the linerboard. In all forms of printing, an excessively rough surface leads to poor or uneven contact between the printing plate and the substrate surface, leading to uneven printing. Poor contact between the bar code image on the plate and the linerboard surface may therefore lead to unevenly printed bar codes. This is strongly influenced by factors such as wood species, pulping technique, and surface forming technology.

In this trial, a set of North American linerboards were printed on a web flexo press with water-based inks, with a variety of press, ink, and plate variables. The samples included brown linerboards, white-top linerboards, and solid bleached kraft linerboards. The goal was to quantify the combined influence of linerboard properties such as formation, smoothness, and water absorbency with press variables such as ink viscosity, printing pressure, and plate hardness.

EXPERIMENTAL

Linerboards

Sample coding

Seventeen different linerboards were printed. These samples included two solid bleached kraft samples (Table I), eight white-top linerboards (Table II), and seven brown linerboards (Table III). The two solid bleached kraft samples, and two of the brown samples were printed on both sides, not just on the manufacturers' recommended (felt) side. This was done in accordance with some commercial practice, where samples are may be printed on either the "wrong" side or on both sides. However, white-top samples were printed only on the white side.

Linerboard sample were given a 3-character code (eg, "AW1"), as follows:

1. First character: Machine code (A - G). In several cases, different grades, or different versions of the same grade, were produced on the same machine.
2. Second character: Grade code. (S, W, and B) "S" refers to solid bleached kraft liner, "W" refers to white-top liner, and "B" refers to brown liner.
3. Third character: Sample number (within the same grade).

Linerboard properties are summarized in Tables I, II, and III. Detailed information on the exact composition of sizing formulations, or on the precise operation of the linerboard machines, are confidential to the suppliers. The samples covered a range of basis weight, bulk, and caliper values, which made it essential to optimize each linerboard separately on the press.

Table I
Solid Bleached Kraft Samples

Sample codes	Surface size?	Caliper, mm	Basis weight. g/m²	R∞, %	PPS roughness, PPS-90 instrument μm	Contact angle (water), degrees	Bristow sorption, A_{80}, mL/m²
AS1	Yes	0.215	192	83.47	2.97	85	8.8
AS1 - reverse side	No	0.215	192	84.23	4.02	75	12.7
AS2	Yes	0.216	188	83.49	3.46	74	11.5
AS2 - reverse side	No	0.216	188	84.25	4.32	82	14.2

Table II
White-top Samples

Sample code	Variable	Surface size?	Caliper, mm	Basis weight, g/m²	R∞, %	PPS roughness, PPS-90 instrument, μm	Contact angle with water, degrees	Bristow sorption, A_{80}, mL/m²
BW1	Furnish	No	0.24	179	78.09	7.46	100	12
BW2		No	0.235	173	72.49	6.95	108	
CW1	Calendering	No	0.257	193	78.21	6.59	101	12.2
CW2		No	0.258	179	77.51	8.47	106	13.8

Table III
Brown Samples

Sample codes	*Variable*	*Caliper, mm*	*Basis weight, g/m^2*	*R∞, %*	*PPS roughness, PPS-90 instrument, µm*	*Contact angle (water), degrees*	*Bristow sorption, A_{80}, mL/m^2*
CB1	*Calendering*	*0.298*	*192*	*23.41*	*8.36*	*90*	*13.6*
CB2		*0.32*	*193*	*23.47*	*10.9*	*109*	*17.0*
DB1		*0.243*	*172*	*22.7*	*7.91*	*103*	*12.7*
EB1	*Two sides of the same sheet*	*0.247*	*168*	*31.45*	*8.52*	*108*	*13.5*
EB1- reverse side		*0.247*	*168*	*34.57*	*8.65*	*108*	*16.5*
FB1		*0.302*	*196*	*23.99*	*11.1*	*111*	*17.0*
GB1		*0.29*	*192*	*24.44*	*9.06*	*98*	*13.8*
HB1	*Two sides of the same sheet*	*0.248*	*168*	*28.44*	*7.43*	*101*	*14.4*
HB1 - reverse side		*0.248*	*168*	*28.08*	*9.01*	*111*	*14.9*

Physical properties — unprinted linerboards

Physical data include bulk and caliper, roughness (Print Surf S-10 value and Sheffield), air permeability (Print Surf), dynamic (Bristow) sorption of water and dynamic IGT sorption. Print Surf measurements were done on the newer Print Surf 90 instrument -- an important distinction, as the results are very different from those obtained with the older Print Surf models. This will be discussed in detail in Appendix A. We also note a fair correlation between Print Surf roughness and air permeability ($R^2 = 0.47$), since in conventional linerboard manufacturing, the smoothest samples are usually the least porous as well, especially for surface-sized material.

The dynamic Bristow sorption is given as the amount of water absorbed at 80 ms contact (A_{80}) between the distribution headbox and the linerboard surface. Although a full dynamic sorption curve requires sorption measurements at contact times between 4 ms and 2 s, we have found [9] that the sorption at a single contact time gives a useful relative scale of absorption.

In the IGT dynamic absorption test, a drop of flexo ink is smeared between a smooth roll and the linerboard on the IGT printability tester. The length of the trace is taken as a measure of the surface absorptivity; a longer trace indicating a less absorbent surface. The printed traces were also useful for visualizing both the degree of ink holdout and the degree of printed mottle.

We note that, although the correlation between the IGT length and the contact angle is good ($R^2 = 0.65$), the correlation between the Bristow absorption and the contact angle is poorer ($R^2 = 0.35$). Similarly, there is a good correlation between roughness and contact angle ($R^2 = 0.54$). As discussed below, this is not a causal relation, and simply reflects the normal conditions of linerboard manufacture.

Trial design

Table IV shows the experimental design for the "many press variables" portion of the trial. Three white-top linerboards (samples BW1, CW1, and CW2) were printed under different press conditions. In addition to printing nip pressure, variables included plate hardness and ink viscosity, as described below. Table V shows the experimental design for the study with all 17 linerboards.

Flexo press and press operation

The press was a Carint Gemini S.12 common impression cylinder press, at the Fox Valley Technical College in Appleton, Wisconsin. The press speed was 400 feet per minute (122 m/min). Hot air dryers were used to dry the ink. The dryer temperatures were 160° F (71° C) after the printing unit, and 140° F (60° C) before the rewind stand.

Table IV
Experimental Design -- Many Press Variables

Linerboard	*Cyan ink*			*Black ink*				
	"Soft" plates		*"Hard" plates*	*"Soft" plates*				*"Hard" plates*
	Ink viscosity, Zahn #2, s		*Ink viscosity, Zahn #2, s*	*Ink viscosity, Zahn #2, s*				*Ink viscosity, Zahn #2, s*
	29	*20*	*30*	*32*	*30*	*27*	*20*	*20*
BW1	✓	✓	✓	✓	✓	✓	✓	✓
CW1	✓	✓	✓		✓		✓	✓
CW2	✓	✓	✓		✓		✓	✓

Ink viscosities are given as the efflux time (s) from a Zahn #2 cup viscometer. According to the supplier's literature, 20 s viscosity ≈ 30 cP, and 30 s viscosity ≈ 70 cP.

Although this is a six-colour press, only one colour unit was used at a time. During the trial, cyan and black inks were printed on different units at different times. The two units had identical anilox cylinders, engraved at 440 lines per inch, with an ink capacity of 5.0 BCM ("billion cubic microns per square inch"). This is equivalent to an ink film thickness of 7.7 μm.

During each run, the printing nip pressure was increased until the first point where the halftone photographic print was uniform to the eye of the press operator. This was designated as the "0" pressure point. Pressure was varied by changing the "squeeze" in the nip: the theoretical overlap (in thousandths of an inch) between the compressible plate and the impression cylinder. A pressure of -1 meant that the nip had been opened by 0.001" (25 μm), while a pressure of +1 meant that the nip had been closed by 0.001".

Plates

Dupont Cyrel and Hercules Merigraph plates were used. Two different types of each were used: Cyrel PLS (designated as "Cyrel soft"), Cyrel HOS ("Cyrel hard"), "Merigraph soft", and "Merigraph hard". These are described in Table VI

Two plates were mounted side-by-side on the press. The Cyrel "soft" and Merigraph "soft" plates were run together, as were the Cyrel "hard" and Merigraph "hard" plates. In that way, we obtained otherwise two identical images side-by-side.

Table V
Experimental Design – Many Linerboards

Linerboard	*Cyan ink*			*Black ink*				
	"Soft" plates		*"Hard" plates*	*"Soft" plates*				*"Hard" plates*
	Ink viscosity, s		*Ink viscosity, s*	*Ink viscosity, s*				*Ink viscosity, s*
	29	*20*	*30*	*32*	*30*	*27*	*20*	*20*
AS1	✓				✓			
AS1 reverse side	✓							
AS2	✓				✓			
AS2 - reverse side	✓							
BW1	✓	✓	✓	✓	✓	✓	✓	✓
BW2	✓				✓			
CW1	✓	✓	✓		✓		✓	✓
CW2	✓	✓	✓		✓		✓	✓
DW1	✓				✓			
DW2	✓				✓			
DW3	✓				✓			
DW4	✓				✓			
CB1	✓							
CB2	✓							
DB1	✓							
EB1	✓							
EB1 - reverse side	✓							
FB1	✓							
GB1	✓							
HB1	✓							
HB1 - reverse side	✓							

With plates of different hardness mounted side-by-side, it is impossible to obtain optimum print quality with both plates. We arbitrarily chose the left-hand (Cyrel) plate to set the pressure for the best halftone quality, so the "Merigraph" plate images were automatically excluded from subjective quality ranking.

Table VI
Plate Properties

Plate	*Designation*	*Hardness, Shore A*	*Hardness,Shore A halftone area*	*Contact angle with water, degrees*
Hercules	*Merigraph "soft"*	*40*	*50*	*84*
Hercules	*Merigraph "hard"*	*45*	----	*73*
Cyrel PLS	*Cyrel "soft"*	*56*	----	*96*
Cyrel HOS	*Cyrel "hard"*	*65*	---	*82*

Inks

Water-based inks were supplied by CZ inks (HAI Multi-Use series). These were run at different viscosities, measured as seconds with a No. 2 Zahn viscosity cup. Viscosities were stable throughout the printing run. The pH values of the inks were between 9.3 and 9.5.

A cyan ink was used to allow quantitative analysis of the amount of ink transferred in the commercial press. Solid printed areas were analyzed for the Cu content, using the X-ray fluorescence technique of Heintze and Kocman [10]. Absolute calibration was provided by neutron activation analysis of the liquid inks and of selected printed linerboards.

Samples printed with the black ink were only used for bar code analysis. The rest of the testing (physical, optical, and subjective) was done on the samples printed with the cyan ink.

Test image

The test image was designed with many challenging features, in order to test the full range of surface properties of these linerboards, as well as the full range of printing variables.

- Solid area: In any printing process, the uniformity of printed solids is probably the first print quality factor that meets the eye. The inclusion of a large area also makes it easier to quantitatively determine the amount of ink on the linerboard.
- Halftone areas: Large halftone areas (5 X 5 cm) were included, at 20%, 40%, 60%, and 80% nominal coverage. These were used as part of the study of quantifying ink transfer, and were also used in the examination of printed mottle.
- Bar codes: Bar codes were printed across the test plate, which would be the normal commercial practice (i.e., bottom of the bar code printed first). Bar

codes were also printed in the direction of printing (i.e, side of the bar code printed first). Readability was measured separately on bar codes printed in both directions.

- Text: Readability of printed text is important in print quality, in large solid text areas, areas of fine print, and reverse-text (i.e., white letters on black or cyan background).
- Halftone photograph. Although not a traditional concern in linerboard printing, halftone photographs are commonplace on higher-quality linerboards — increasingly, in process colour. The monochrome Paprican test image "Chess Player" photograph was used.

Evaluation of Printed Samples

Bar code testing

For each printing condition, the bar codes on 100 prints were scanned with a commercial, hand-held bar code scanner (Wedge.one CCD model CF-1KB). With four bar codes printed across the plate and five printed vertically down the plate, for each printing condition there were respectively 400 or 500 bar code readings attempted. Successful readings were automatically entered into a computer, and the pass/fail rate was recorded. Incorrectly read numbers were extremely rare. Bar codes were either read successfully or not at all.

Image analysis of the individual bars was done, in order to relate success or failure in bar code reading to factors such as ink spreading, ink density, and surface defects in the linerboard. The bars were imaged with a Leitz Makroscope onto a CCD video camera attached to a Noesis image analyzer. A narrow, medium and wide bar was measured on each code impression. The width, raggedness, and average print density were measured for each bar.

Subjective testing

A set of 64 prints of the Paprican test image were mounted and framed on neutral grey cards so that only the picture could be seen. Only prints from the white-top boards were used. The prints were presented to each judge in random order and the judge used the *merge sort* [11] technique to sort the prints into rank order from best to worst. Since different judges placed each print into slightly different rank positions, the ranks assigned by twenty judges to each print were averaged. Most of the images had been printed on the "Cyrel soft" plates, but a few were printed on the "Cyrel hard" plate.

Image analysis

The uniformity of the solid areas was measured using the Paprican Microscanner and expressed as specific perimeter and contrast intensity [12]. Some of the brown boards were too opaque for us to measure the formation on the Microscanner, so the same indices were measured on all the boards at the same magnification using a Noesis image analyser. The boards were transilluminated with a 250 W quartz halogen photographic flood lamp through a heat filter, and a black curtain protected the surface from reflected light. The illumination was uniform over the 30 mm by 40 mm field of view, A Zeiss Tessovar lens system fed the image to a monochrome CCD video camera.

Evaluation of surface contact
A device was built that permitted us to press the paper surface against a glass prism at a pressure of 1 MPa (representative of flexo printing pressure) and to view the locus of points in close physical contact between the paper and glass. Behind the paper was a rubber PPS backing, a cork PPS backing and a steel surface in that order. The combination of backings reduces edge effects and produces a uniform pressure profile as confirmed with pressure sensitive Fuji film. A 10 mm x 10 mm portion of the contact area was viewed through a 105 mm focal length Nikon macro lens and a video camera. The video fed into a Joyce-Loebel Magiscan image analyser at 20 μm picture point resolution, but only qualitative results are reported here.

RESULTS AND DISCUSSION

Observations of optical contact in the Chapman tester
At the resolution of a single fibre's width, about 80% of the surface of the solid bleached kraft board was in optical contact with the prism at a pressure of 1 MPa, while only about one third of the surface of the brown board made such contact. About half the surface of the white-top boards made contact and the pressure was insufficient to crush any wire-mark that may have been present. Although physical contact at the scale of fibre-crossings may have been sparse, most regions as large as a halftone dot would have multiple points of contact. As long as the ink could spread on the paper surface, it could compensate for some deficiencies in contact. The exception is the wire-mark that is visible in some of the halftone images used in the subjective ranking study.

We also pressed the flexographic plates against the prism. Well below the 1 MPa pressure level the halftone dots of the soft plate bent, expanded, and in some cases broke off. At 1 MPa, the optical contact area greatly exceeded the nominal coverage area of each halftone region. The halftone dots on the hard plate exhibited minimal distortion and no visible damage at a compression of 1 MPa*. Several regions of the soft plate were pressed against the prism with the same

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* However, during normal press operation, the opposite is true: dots on the hard plates are more susceptible to damage, although they also deform less under nip pressure.

rubber backing as used on the paper and with a plain metal backing. No matter what backing we used, we observed a formation-like mottle to the optical contact that we attribute to nonuniform curing of the photopolymer in the plate. Such variations in the hardness of the plate can lead to formation-like print mottle that appears in the same location on successive prints.

Bar Code Readability

We tried to correlate a large number of press variables with the bar code readability. For the same linerboards printed under different conditions, no trends could be found between bar code readability and press variables such as ink viscosity, printing pressure, and plate hardness.

The distribution of bar code readabilities were done at four different printing pressures: P = -1, P = 0, P = +1, and P = +2. The results at P = 0 were indistinguishable from those at P = -1 and P = +1. However, readability across two pressure intervals *was* significantly different. The poorest readability and the broadest distribution in readability results were at P = -1 and P= +2 (i.e, the lowest and the highest pressures).

In general, we found that bar code readability is surprisingly forgiving of press conditions, with the exception of printing pressure. No statistically significant trends could be seen between bar code readability and the ink viscosity or plate hardness. There was no correlation between readability and factors such as the width or raggedness of individual bars. Bar codes were consistently readable as long as the bars were intact, and free from voids and splotches.

As expected, bar code readability was also greater for bar codes printed across the test plate, which would be the normal commercial practice. Bar codes printed in the direction of printing (i.e, side of the bar code printed first) were less readable.

However, readability was poorer when bars were not properly printed. Bars that have widened without severe distortion or overlapping with their neighbours are still readable. Bars are subject to "voids" (gaps within the printed area of a bar) and "blotches" (stray ink filling in the spaces between bars). Voids were particularly common for bars printed with excessively low pressure.

The most interesting relationship with a linerboard property was between bar code readability and the board's contact angle with water. This is shown in Figure 1, where the readability values were all taken at the "optimum" printing pressure (pressure "0") with the Cyrel "soft" plates, Shore A hardness of 56. There are two regimes for bar code readability. For contact angles of less than 90°, bar codes are readable nearly 100% of the time. As contact angles increase past 90°, the percentage of successful bar code readings decreases rapidly.

It is even more interesting to note that success or failure appears to be independent of board type. Some smooth white-top liners showed poorer bar code readability, and also had contact angles with water of greater than 90°. On the other hand, some wettable brown liners, with contact angles less than 90°, showed excellent readability. This contradicts the conventional wisdom [7], which states that bar codes should be less readable on dark board. From this we believe that the contrast between printed and unprinted areas is much less important than previously assumed. As long as the water-based ink can sufficiently spread to fill in gaps (without creating splotches) the bar codes are readable.

In Figures 1A and 1B, the R_∞ and Print Surf values respectively for the brown samples have been inserted on the graph. This is to show that the conventional wisdom regarding roughness and brightness of the board does not seem to hold. Some less readable brown samples are smoother and brighter, along with being less wettable. The browns with the best readability also have the best wettability, despite being rougher and darker.

Subjective evaluation of halftone print quality
Halftone images printed with Paprican's standard test photograph on white-top liner were subjectively evaluated. Deviations from the optimum printing pressure seem to be the primary cause of printed mottle. For example, an increase of only 0.001" (25 μm) in the nip clearance caused severe mottle — so much so that such prints were automatically excluded from the subjective study.

Since plates of different hardness (Dupont Cyrel and Hercules Merigraph) were always printed side by side, and the halftone image was always optimized for the harder of the two plates, the image printed with the softer (right-hand Hercules Merigraph) plate was automatically rejected, due to the obviously greater amount of printed mottle and dot gain. The amount of dot gain was not trivial: for the non-optimized image, the coverage of the nominal 20% halftone area was greater than 90%; representing dot gain far greater than the problem levels of other printing processes.
While the halftone image printed with the right-hand plate was rejected, the bar codes and solid prints were still analysed.

Sheffield roughness (the most commonly-used roughness in the linerboard industry) correlated with the visual ranking with $R^2 = 0.48$. The extended range Print Surf 90 air leak roughness tester also correlated with $R^2 = 0.48$ There was one outlying sample, with the lowest R_∞. this may have contributed to its poor subjective rank. While other samples with comparable R_∞ are less glaring, they fall in line better when their reflectance is taken as a separate regression factor. In Appendix A, we show that the more traditional Sheffield test and the newer Print

Surf 90 both correlate with the visual ranking. This is not the case for the older Print Surf 78 instrument, as discussed in Appendix A.

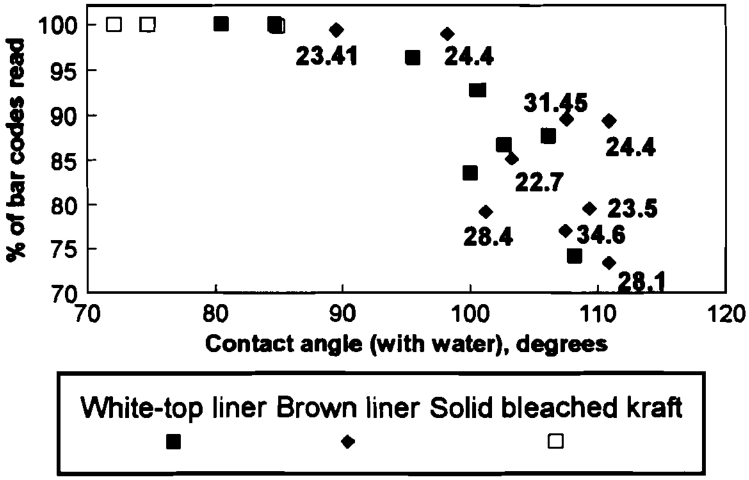

Figure 1A Bar code readability as a function of contact angle with water. All samples printed with "Cyrel soft" plates and cyan ink (viscosity = 30 s), at the "0" pressure setting. White-top (■), brown (♦), and solid bleached kraft (□). R_∞ values for the brown liners are indicated.

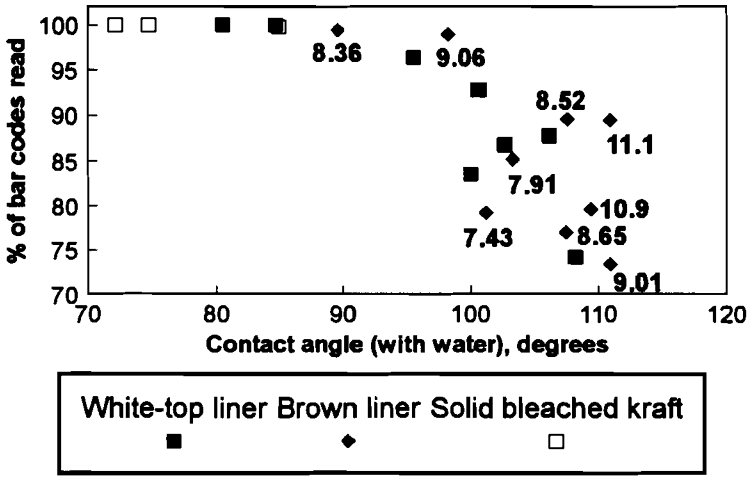

Figure 1B. Bar code readability as a function of contact angle with water. All samples printed with "Cyrel soft" plates and cyan ink (viscosity = 30 s), at the "0" pressure setting. White-top (■), brown (♦), and solid bleached kraft (□). For the brown liners, Print Surf values are indicated.

The subjective ranking of the largest group of samples ("Cyrel soft" plates, ink viscosity = 30 s) correlated with the extended range Print Surf-90 surface roughness and reflectance of the paper, with $R^2 = 0.88$, according to the following empirical relation, obtained from the multilinear least squares regression fit of ranking to roughness and R_∞.

$$Ranking = 80.7 + 4.21 * Print\ Surf\ roughness - (1.17 * R_\infty) \quad (1)$$

In Figure 2, rank is plotted against the best fit (roughness and R_∞) function. The best-ranked samples (lowest rank numbers) were those printed with the hardest plates ("Cyrel hard", Shore A hardness of 65, Table VI), with an ink viscosity of 30 s. Informal comments from judges after the completion of their rankings indicated that different amounts of non-uniformity had influenced their judgements.

The lowest-ranked samples combined the softer* plates with the lower viscosity ink (ink viscosity = 20 s). The best-fit PPS and R_∞ values are not identical for nominally identical linerboards, due to small roll-to-roll differences among the samples.

Dot gain was greater for the softer plate, due to the greater lateral spreading of the ink, reducing image quality. This was seen from density measurements in the 20% and 40% halftone areas. Dot gain was greater still for the lower viscosity ink, due to the even greater lateral spreading of this lower viscosity ink. The best combination for print quality was the hardest plate (65 Shore A hardness) and the highest viscosity ink**.

Print non-uniformity and formation

For the softer plate, there was no correlation between subjective print quality and the surface formation of the unprinted board. We believe that this may be

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* In Figure 2, when we refer to "soft" plates, we refer to images that were optimized for the soft Cyrel plates -- not to the non-optimized "Merigraph soft" (right-hand) plate images that have already been rejected.

** Caution is required in defining optimum plate "hardness". Conventional wisdom tells us that softer plates give better image quality. This is true within reason, especially for solid areas. However, an excessively soft plate leads to reduced print quality, due to excessive dot spreading. On the other hand, a "hard" flexo plate (65 hardness) would still be considered as a fairly "soft" letterpress plate.

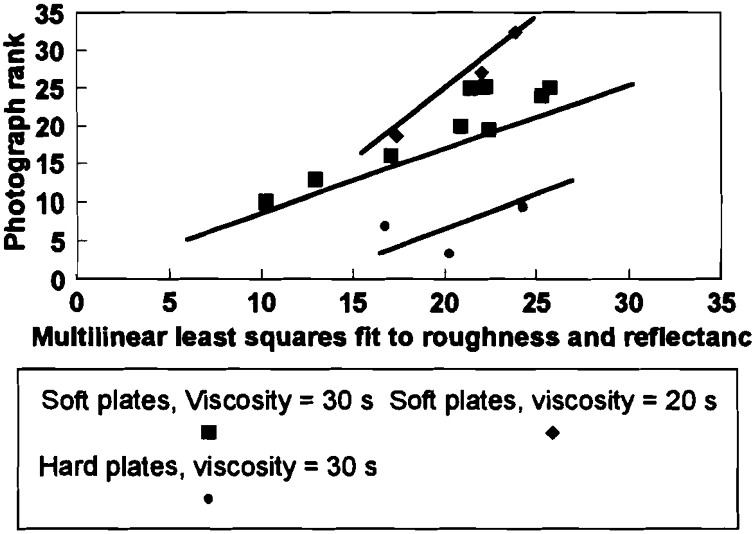

Figure 2. Subjective rank of test photograph as function of the multilinear least squares fit to the PPS-90 roughness and the reflectance. Linerboards were printed by: soft plates and low ink viscosity; soft plates and high ink viscosity; hard plates and high ink viscosity. Three linerboards were printed under all three conditions.

generally true for soft plates, but not for hard plates, as shown in a separate report [13]. A further cause of printed mottle, again with the hard plates, is improper development of the plate, leading to zones of different cross-linking of the photopolymer and so to zones of different hardness in the plate (as seen in the Chapman tester). This would explain mottle patterns that repeated themselves from print to print*.

Quality of printed solids

Past work on printing newsprint with water-based flexo inks showed at least two competing effects: roughness and surface chemistry. Across a very wide range of roughness, print density was controlled by roughness, with rougher newsprints giving lower print density [14]. However, at constant roughness, both ink transfer and ink penetration increased with increasing water absorbency [15].

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* All of these samples were calendered with conventional hard nips. We might expect that, based on experience from publication printing, soft calendering would also ease mottling problems.

How much ink is transferred to the linerboards? What is the final distribution of the ink at or near the surface? What is the final print density? These are all critical, interconnected questions.

The influence of board properties such as roughness and contact angle on the amount of ink transferred was surprisingly small. As shown in Figure 3, the amount of ink transferred to the brown and white-top linerboards covered a wide range, and there is no trend apparent for the different types of linerboard.

Figure 4 shows the print density (cyan ink) for the linerboards as a function of surface roughness. Unless noted, all the measurements were taken with the "Cyrel soft" plates. Across the entire range of samples, print density decreases with increasing surface roughness, although the solid bleached kraft and white-top liners fall into one group, and the brown liners fall into another. Although print density and roughness follow the order solid white > white-top >> brown, there is no correlation between print density and roughness within a given class. The implication is that within a given class, smoothness is important for halftone dot quality, but not for solid area quality, at least with the softer plates.

Figure 4 also shows that the print density on the brown liner is much lower than for the solid white and white-top samples. This arises from the normal procedure of correcting the measured value for the darker colour of the underlying linerboard by subtracting the substrate's optical density. This is justified since the darker colour of the underlying substrate gives an apparently darker image. Furthermore, any pigment that penetrates such a dark material is "lost" to a surface reflectance measurement, while it would still contribute if it had penetrated a white material. The question, however, still remains, as to whether the much lower print densities of the brown linerboards represent a true optical effect, or simply an artefact of the measurement technique.

How is the ink distributed on or near the linerboard surfaces? Consider samples of different composition, but made on the same linerboard machine. Figure 5 shows cross-sections of solid prints of samples DB1, DW1, and DW3. These are (respectively) brown liner, white-top liner without surface sizing, and white-top liner with surface sizing. The amount of ink visible in the cross section of the brown liner is apparently less than that of the white-top liners. However, the amount of ink actually transferred is the same for all three samples (3.0 ± 0.1 g/m^2). This may provide further evidence of the optical "hiding" power of a brown linerboard surface.

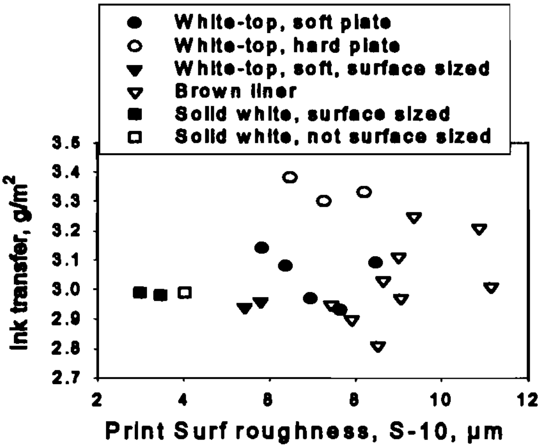

Figure 3 Amount of ink transferred to the linerboards (solid areas) as a function of Print Surf roughness

This presents a quandary. For these three samples, we have already stated that the amount of ink on each linerboard is the same. Yet where has the ink gone? We know that the ink is there, from chemical analysis. Yet on the brown liner, reflectance measurements do not "see" this ink. Nor can the ink be seen to have penetrated within the sheets. One possibility is that, since the brown linerboards are both more hydrophobic and more mottled, the ink is held out at the surface, but

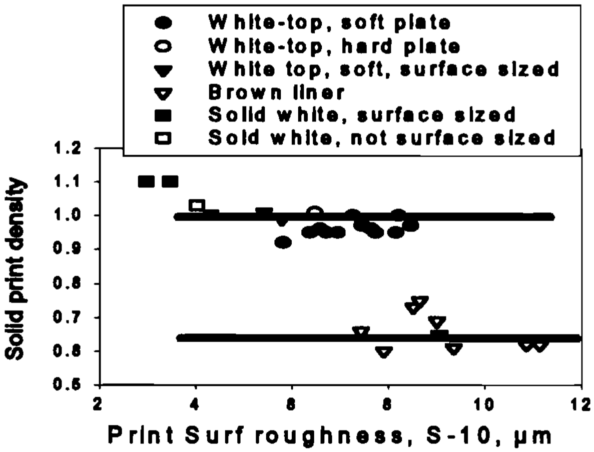

Figure 4 Solid print density as a function of Print Surf roughness

is held out inefficiently, with "islands" of greater or lesser amounts of ink near the surface.

The highest print density among the white-top samples belongs to samples DW3 and DW4, which were the only surface sized white-tops. Samples DW1 and DW2 -- produced on the same machine, but without surface size -- showed only a slightly reduced print density. How did the surface sizing improve the print density? Was the improved print density due to the surface chemical influence of the surface sizing, due to the formation of a barrier layer, or to improved smoothness? An extra complication exists since roughness and contact angle are well-correlated ($R^2 = 0.54$), as the smoother boards tend to be the ones with starch on the surface.

Figure 4 also shows print density as a function of contact angle. Again across the entire range of samples, print density is lower for more hydrophobic surfaces. The same comments apply as for the print density/roughness relationship.

Figure 6 illustrates the "printing efficiency" (print density per gram of ink) as a function of roughness and of contact angle. While there is an overall trend to decreasing printing efficiency as the boards become rougher and more water-repellent across the whole range of linerboards, within each grade, there are no correlations, as with the print density alone*.

In Figure 6, the samples with the highest printing efficiency were those with surface sizing. Within the solid white samples, the surface-sized side of the solid white sample gave the best printing efficiency, while the untreated side of the same sample gave a lower value. Similarly, within the white-top samples, the best printing efficiency belonged to the only two surface-sized white-top samples, DW3 and DW4.

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* Similar results are obtained for printing efficiency vs. Bristow absorption and for printing efficiency vs. IGT length.

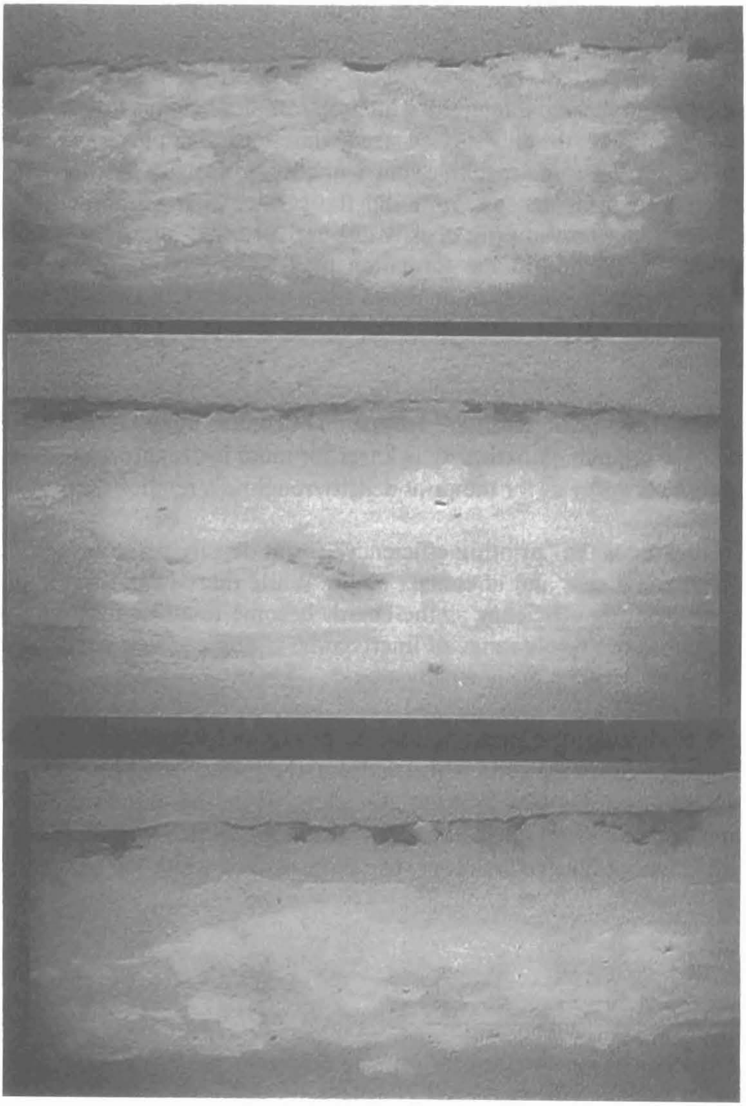

Figure 5: Cross sections of linerboards made on the same machine, as described in the text. Top: Brown liner; middle: white-top liner; Bottom: Surface-sized white-top liner.

That penetration is important can also be seen from visual examination of the Bristow absorption traces. With the same amount of dyed water transferred to the different linerboards, there are obvious differences in the intensity of the colour, which we can ascribe to the influence of the surface sizing agent on holdout and penetration.

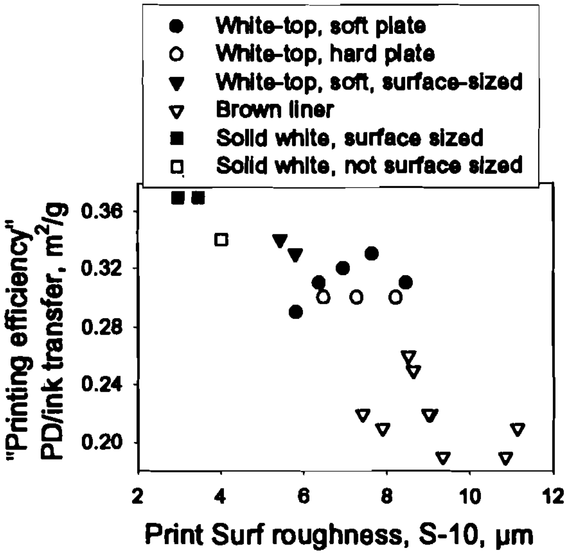

Figure 6 Solid area printing efficiency, or print density per gram of ink, as a function of Print Surf roughness.

Smoother boards tend to have lower contact angles (R^2 = 0.55) due more to the conventions of board manufacture than to any causal relationship. At the same time, the "true" contact angle is complicated by questions of the board roughness, and of the value of the contact angle (i.e., greater than or less than 90°). However, there was also a good correlation (R^2 = 0.65) between contact angle and IGT dynamic absorption, which was previously shown to be related to flexo print quality [3], so it is reasonable to use contact angles as a benchmark for this work.

Further work is required on well-controlled, lab-prepared samples to separate the effects of roughness and surface chemistry. Based on our past work on flexo printing of newsprint, and based on the visual examination of the surface-sized linerboard samples, it would appear that both smoothness and wettability are necessary, although the relative importance of each is still to be determined, along with the contribution of the barrier layer (if any).

Ink transfer

Figure 7 shows the solid print density, ink transfer, and printing efficiency as a function of printing pressure. We see that there is an increase in ink transfer to the solid area with increasing printing pressure. At the same time, however, there is a *decrease* in solid print density with increasing pressure, leading to a poorer printing efficiency. We propose that this behaviour results from the forced penetration of the ink into the linerboard surface.

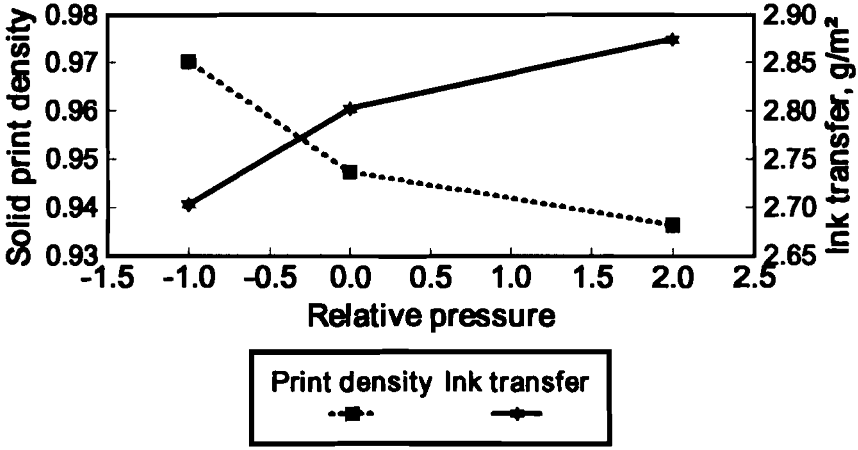

Figure 7 Influence of printing pressure on ink transfer and print density.

Text Readability

The area used to determine text readability consisted of simple text decreasing in size from 18 point to 6 point, in both regular and reverse text (i.e, unprinted "white" text on a printed black or cyan background). Readability was ranked by a single judge, who gave scores from 0 (completely unreadable) to 8 (best readability). Samples were evaluated with all printing pressures, linerboards, ink viscosities, and plates.

In general, all normally printed text (black or cyan letters on an unprinted background) was readable, although a few scores were reduced because of relatively slight readability problems at low printing pressures, due to skipped type. On the other hand, the reverse text was much more demanding. Since print quality had been optimized for the harder of the two side-by-side plates, in nearly all cases, the reverse text printed with the softer of the two side-by-side plates was completely filled in and unreadable. Even for the harder of the two plates, the readability was still very sensitive to printing pressure, with the text filling in and becoming less readable at pressures greater than the optimum. At less-than-optimum printing pressures, the reverse text was readable, although the text areas usually contained unprinted zones due to loss of contact with the plate.

SUMMARY AND CONCLUSIONS

The flexo print quality of linerboard depends on a variety of surface properties; the exact surface property depending on which print quality factor is being considered. The subjective quality of a halftone photograph increased as the board became smoother and brighter, and also increased with a harder printing plate and a higher viscosity ink. Bar code readability was surprisingly unaffected by major variables such as ink viscosity, plate hardness, and board roughness. Contrary to a well-established conventional wisdom which states that bar codes printed on very dark linerboards are more difficult to read [7], readability was independent of the linerboard brightness. On the other hand, bar code readability *was* poorer on more water-repellent boards, or with inappropriate printing pressures (whether too high or too low).

Solid print density and ink holdout decreased as the linerboards become rougher and more hydrophobic, but only when considered across the whole commercial range from brown to white-top to solid bleached linerboard. Within any single grade (solid bleached kraft, white-top or brown) roughness and water absorbency had little or no influence. Surface sizing was effective at increasing ink holdout.

While older models of the Parker Print Surf cannot measure rough linerboards, the new model PPS-90 is acceptable.

Samples with different moisture contents showed no apparent difference in print quality and in benchtop testing. In the case of commercial print quality, this may have been due to the overriding influence of other board properties, while for lab testing, the differences were probably removed by conditioning under constant temperature and humidity.

Further work is needed to separate the effects of board roughness and wettability from each other, especially since in normal commercial production the two factors are interrelated. However, based on our past work on flexo printing of newsprint, and based on the visual examination of the surface-sized linerboard samples, it would appear that both smoothness and wettability are necessary, although the relative importance of each is still to be determined, as is the precise contribution of the surface size barrier layer.

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APPENDIX

Useful range of the Parker Print Surf air leak roughness apparatus
The Parker Print Surf air leak roughness tester is commonly used to predict the print quality of paper. In particular, it is commonly used as a quality control tool in the manufacture of newpsrint and uncoated groundwood specialties.

For the older, and more common, Print Surf 78 model, the manufacturer states that the calibration cannot be extended above a roughness of about 6.5 μm, and so measured values are not reliable above this figure. This upper limit effectively excludes many rougher grades, such as some linerboards and wood-free fine papers. Therefore, the Sheffield tester is more common in the linerboard industry.

The more recent Parker Print Surf 90 model is designed to examine samples across a wider range of roughness. The roughness of these linerboards was measured with the two Print Surf instruments, and the results compared to other test results.

Figure A-1 shows the roughness from the extended range Print Surf 90 model plotted as a function of the data from the old Print Surf 78. All the linerboards from our trial are included in this figure, including brown linerboards, white-top linerboards, and solid bleached kraft liners. Up to a Print Surf value of about 6 μm, the two sets of data coincide. Past about 6 μm, the roughness values from the old Print Surf level off, meaning that there is no discrimination among the rougher samples, while the extended range Print Surf 90 can discriminate among the samples.

As shown in Table A-I, the correlation R^2 between the subjective ranking of the white top linerboards and the old Print Surf roughness was only 0.27. On the other hand, R^2 between subjective ranking and the new Print Surf roughness was 0.43, while R^2 between ranking and Sheffield roughness was 0.48. When roughness and brightness are correlated jointly with subjective ranking, there appears to be a

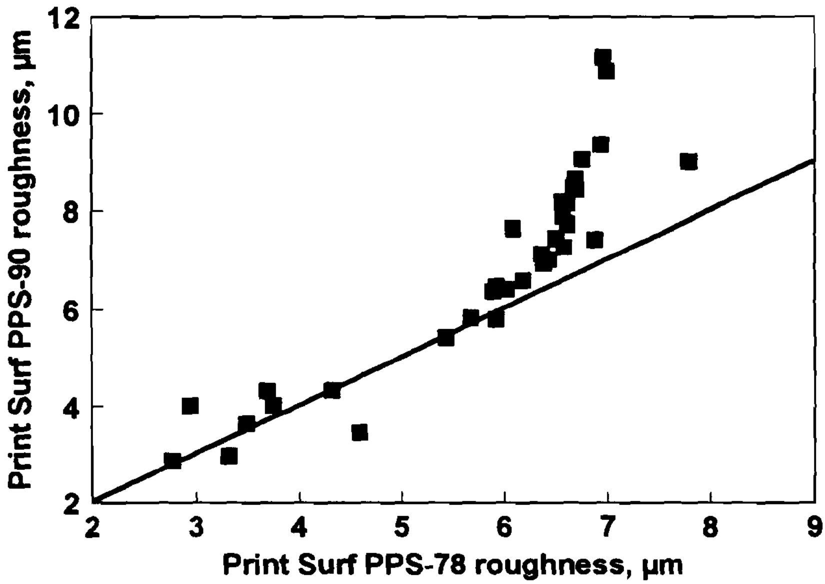

Figure A-1. New Print Surf (PPS-90) roughness as a function of the old Print Surf (PPS-78) values, The 45° line of equal values is shown. Note the greater discrimination of values by the new Print Surf instrument compared to the old one at high roughness levels.

slight advantage of the new Print Surf over the Sheffield roughness.

Table A-I
Correlations with subjective ranking of white-top linerboards

	Correlation with roughness, R^2	*Correlation with roughness and brightness, R^2*
Sheffield	*0.48*	*0.66*
Old Print Surf	*0.27*	*0.65*
New Print Surf	*0.43*	*0.88*

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