Offset Print Quality of Uncoated Mechanical Printing Papers: Results of a Commercial Heatset Offset Trial

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Keywords: Offset, Paper, Papermaking, Quality, Testing

Twenty-four uncoated mechanical printing papers, from newsprint to SCA, were printed by the heatset offset process. Correlations between subjective ranking and paper properties were much better on the top side of the samples. Among the paper surface factors examined, the total length of fibre exposed on the paper surface, or the "speed bumps", gave the highest correlation with the subjective ranking. In general, correlations between ranking and paper properties were much poorer on the bottom side of the sheet. When the same samples were printed by gravure, all on the same side of the press, the bottom side correlations were less good. Therefore, top to bottom differences in correlations are an inherent paper structural problem which should be addressed in future work. Among print properties, only ink trapping gave a good correlation with subjective judgements. Optical and confocal microscopy showed the detrimental effects of surface pits and coarse surface fibres on ink transfer, halftone dot structure, and print quality.

Introduction

The influence of paper properties on print quality has been studied for many years. This is particularly true for newsprint and mechanical printing grades. However, much of the previous information in the literature deals with conventional newspaper printing [e.g., 1,2]. At the same time, the expectations of printers and print buyers have increased greatly. One consequence of these quality expectations has been the trend over the last 10–15 years to either upgrade existing newsprint

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machines or to install new machines to produce higher value-added products, in particular soft-calendered and supercalendered grades.

For papermakers, there is a never-ending need to close the loop among the following factors: raw materials, papermaking variables, printing press technology, and customer demands. All of these factors in turn affect the final print quality. The current report is part of a series on commercial-scale printing trials using a variety of grades of paper and board, with different printing processes. Trials include printing of newsprint by letterpress [2], lightweight coated paper by heatset offset printing [3], linerboard by water-based flexography [4], and woodfree fine papers by heatset offset printing [5]. The same samples printed in this trail were also the subject of a parallel gravure printing trial [6].

Increasing customer expectations of improved print quality, and an ever-increasing number of impressions between press washups make the search for optimum paper performance never-ending. To aid us in this task, we have at our disposal physical, electronic, and subjective testing tools that did not exist ten or even five years ago.

The common theme of these reports is not simply to evaluate print quality, but to identify the measurable surface properties related to print quality. Part of this includes identifying or developing predictive testing methods that can be applied in the paper mill.

Although paper formation is not as critical in offset printing as it is in letterpress and gravure, good formation is still needed for optimum print quality, free from mottle. Aside from formation and a low linting performance, the main criteria for different grades of uncoated mechanical papers for heatset offset printing are smoothness and gloss. Gloss normally refers to the paper gloss before printing as well as to the printed ink gloss after printing. However, gloss may also refer to the *retention* of gloss by the paper after printing. Due to the irreversible swelling of fibres — especially poorly-developed mechanical pulp fibres — by the water and heat of the heatset offset process, the gloss after printing can be reduced to an extent that is objectionable to the customer.

In this trial, 24 samples were printed by the heatset offset process at the Rochester Institute of Technology. The samples included conventional newsprint, soft-calendered newsprint, machine finished newsprint, and supercalendered grades including SCC, SCB, and SCA. Physical and optical properties of the papers were measured and compared to measurements of the optical properties of the final prints, and to the subjective ranking of print quality. Confocal and optical microscopy were also used to help characterize the printed and unprinted surfaces.

Experimental

Paper samples

Samples are described in Table I, along with their nominal grades. Paper properties are also given in Table I, including roughness (Print Surf), gloss, formation, etc. In all cases, "top" and "bottom" refers to the samples as they were printed on the top and bottom units of the press, which may not necessarily be the same as the "side" of the paper machine on which they were produced, depending on the winding practices at the mills of origin.

Figure 1. "Musicians" test photograph [7].

Test form

The test form contained a variety of features, combining areas for instrumental testing (of colour, contrast, gloss, trapping, and sharpness) with test photographs for subjective testing. The test photographs are referred to as the "Musicians" (Figure 1) and the "Candlesticks", and are part of an ISO standard [7]. For this paper grade, the Musicians image was evaluated at screen rulings of 100 and 150 lines per inch, and with stochastic screening with a nominal dot size of 21 μm. In addition, the Candlestick image at 150 lpi was also used in the subjective rankings. Halftone dot areas were printed for the four colours (black, cyan, magenta and yellow), at 25%, 50%, 75%, and 100% (solid) coverage. Partially overlapped solid areas were printed, to allow us to measure both solid print density and uniformity. In addition to the usual black solid (i.e., printed with black ink), there was also a 4-colour black solid, obtained from the overlap of cyan, magenta, yellow, and black inks.

Press

There were 24 unique samples. The three SCA samples were printed twice, with high tack and low tack inks. Two other samples were run twice using the low tack ink; thus giving a total of 29 printed samples.

The samples were printed on a Harris M1000B press at the Rochester Institute of Technology. The press speed was 1200 feet per minute (6 m/s). The temperature of the web at the exit of the drying oven was 270 °F (132 °C) for the high tack ink used on the SCA grades, and 260 °F (127 ° C) for the low tack ink. Between 8,000 and 10,000 impressions were run from the each roll. The optical densities of the printed inks were adjusted to the following, conventional values: black = 1.05; cyan = 0.90; magenta = 1.0; and yellow = 0.85.

After each run, clear adhesive tape was used to remove lint, dust, and other debris from the top and bottom side blankets from the first (black) colour unit, for later analysis. All blankets were then washed before the next sample was spliced in.

Inks

At the start of the trial, the SCA papers were printed with a set of relatively high-tack process colour inks formulated for uncoated, supercalendered papers (Sun Chemical "Supercal"). The tack values were: black, 8.0; cyan, 7.0; magenta, 6.0; and yellow, 5.0. Next, all the papers, including the SCA samples, were printed with relatively low tack inks, designed for the weaker surface of newsprint (Sun Chemical Heatset News; tack values of: black, 6.5; cyan, 6.0; magenta, 5.5; and yellow, 5.0.)

Sample testing

Visual ranking

The printed samples were visually ranked. These rankings were then used to determine the paper and print attributes (or flaws) that most influence the judgements. The merge-sort method [8] was used to rank the samples, as it is easy to teach and very efficient for large sample sets. By including replicates, the consistency of each judge was determined.

For each set of prints, 20 judges with varied experience, age and areas of expertise were asked the same question: *"Which samples do you prefer?"* Judges were instructed merely on the mechanics of sorting, and care was taken to avoid any hints that might direct a judge's attention to particular image features or criteria. There were no judges with a specific professional bias (e.g., advertising designers or printers).

Physical measurements:
Optical properties of the print including print mottle, print sharpness and contrast were measured. Also measured were paper properties that have a potential influence on the printing properties, as discussed in detail below.

1. Parker Print Surf (PPS), and Bristow's compressibility. Surface roughness was measured with the Print Surf at three different pressures: 5, 10, and 20 kgf/cm^2 (nominally 0.5, 1.0, and 2.0 MPa). The Print Surf value at a single pressure is used to express the paper surface roughness. Print Surf values at different pressures can be used as a measure of paper compressibility. We used a variant of Bristow's technique [9].

   Bristow's approach assumes that for papers with the same Print Surf reading, differences in print quality result from differences in compressibility. He defined a "pressure requirement" as the hypothetical pressure on the Print Surf head that would be needed for a given Print Surf reading, so that a higher pressure required to obtain the target roughness is an indication of a less compressible sheet. In our case, we chose a Print Surf roughness of 1.0 μm as the target value. The pressure requirement to obtain this roughness was then calculated from the roughness values at 5 and 10 kgf/cm^2 by extrapolating the experimental values of roughness vs. applied pressure. This pressure requirement produces information combining surface roughness and compressibility.

2. *Optical roughness*: The device developed at Paprican to measure fibre rising in a sample [10] was used to measure the optical roughness, in terms of the fibre length exposed above the paper surface, before and after applying 1.5 g/m^2 of water using the flexo applicator roll on the IGT A1C2-5 printability tester [11]. The apparatus illuminated the paper surface symmetrically at 6.5° above the horizontal. Glancing-angle illumination casts shadows inside indentations in the surface while symmetric illumination minimizes the shadows cast by protrusions. The paper was viewed perpendicular to its surface by a video camera. Image analysis techniques were used to highlight and quantify fibres and fibre segments sticking out of the surface. These protrusions permit light to enter the sheet and diffusely reflect. Protruding fibres appear as bright lines when viewed normal to the surface.

3. *Ash content*: The amount was determined gravimetrically following ashing of the sheet at 925°C, according to the CPPA standard [12].

4. *Paper formation index*: This was measured on the Paprican Micro-Scanner, and is calculated from the ratio of specific perimeter to the standard deviation of the paper's mass density. The index is therefore proportional to the graininess of the flocs, and inversely proportional to the contrast of the flocs [13], so a higher number is better.

5. *Print mottle*: The print uniformity index, which is the ratio of the specific perimeter of the solid print structure to the optical density deviation within the print, was also measured on the Paprican Micro-Scanner. This index indicates how small or grainy the mottled areas are, as well as how uniform their densities are. The pixel size is 63 μm, which is on the scale of several halftone dots.

6. *Print sharpness and contrast*: This was assessed using the method developed by Nguyen *et al.* [14] which uses a PC-based image analysis system and Visilog software.

7. *Halftone dot features*: The mean and variation of dot gain and circularity were measured at 4μm resolution using Visilog software. Halftone dot areas (25%) were measured using the Paprican Inkscanner [15]. Each halftone print is illuminated with diffuse red light (660 nm) and imaged with the camera of a Paprican InkScanner, with 5μm optical and electronic resolution. The diffuse illumination provides a relatively artifact-free image of ink distributions on the paper surface. Figure 2 show two histograms, for a well-ranked SCA and a poorly-ranked newsprint. Each histogram contains two peaks, corresponding to the reflectance of the inked areas and the reflectance of the unprinted paper between the dots. So-called "optical gain" lowers the between-dot reflectance when the dot spacing is comparable to the distance light diffuses within the paper. Compared to the SCA sample, we see that the reflectance distribution of the newsprint inked surface broadens and moves toward higher values when the ink layer is discontinuous or contains thin regions. The difference in reflectance between the intra-dot (dark) reflectance and the inter-dot (light) reflectance is reported as an effective contrast.

8. *Optical gain characterization*: Each test sheet was fed through a LaserJet™ printer, and printed with several regions of halftone dots. To aid sample feeding through the printer, many of the papers were glued at the leading edge to a fine paper sheet. After printing, the glued portion was cut off. The lightest two regions achieved coverages of 42% and 62% as determined by image analysis, and the coverage was the same for each paper sheet. We then

calculated the apparent reflectance of the inter-dot unprinted paper from a print with ink coverage "c" using the following relation:

$$R_{print} = c\, R_{toner} + (1-c)\, R_{paper} \tag{1}$$

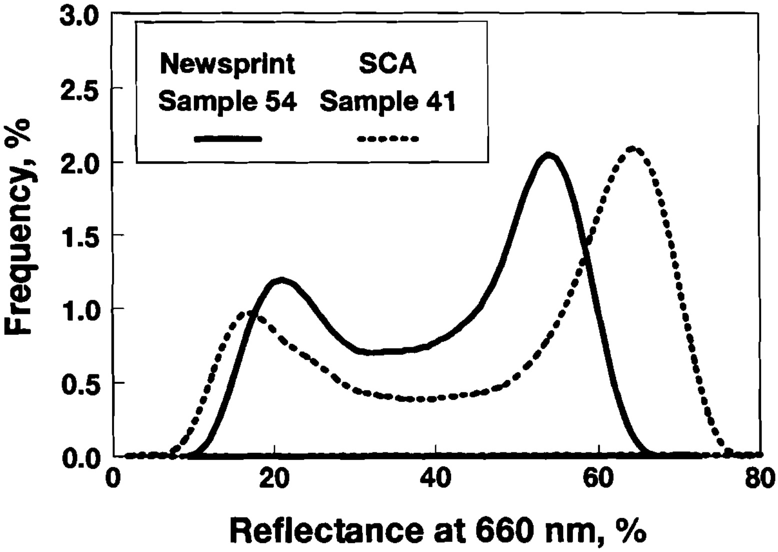


Figure 2 Histograms showing reflectance spectra of 25% halftone areas for sample 54 (a poorly-ranked newsprint) and sample 41 (a highly ranked SCA). The low reflectance region corresponds to the inked area, and the high reflectance region corresponds to the unprinted area. Note that the inked area for the newsprint becomes less dark, and the unprinted area becomes darker, compared to the SCA. This is another demonstration of contrast differences in the final prints.

This time, we used the more perceptually relevant L* colour coefficient instead of the reflectance. Since light diffusion reduces the inter-dot reflectance more when higher coverage shrinks the inter-dot space, the difference between the apparent inter-dot reflectance at 42% coverage and at 62% coverage is even more characteristic of optical gain than the inter-dot reflectance itself. We used the absolute difference in inter-dot L* values and the fractional difference in L* values as separate "Yule" variables for regression.

9. *CLSM Analysis*: Samples were imaged in a Leitz confocal laser scanning microscope (CLSM). Starting from a zero-point surface reference plane, quantitative measurements were made of the exposed fibre areas at different depths, from 0 down to approximately 30 μm below the reference plane.

10. *Colour trapping*: Wet trapping (the ability of one ink to transfer on top of another) was quantified by the method of Preucil [e.g., 16], who developed the equation that is most commonly used for trapping calculations:

$$\%Trapping = \frac{D_{overprint} - D_{first\ colour}}{D_{second\ colour}} \times 100\% \qquad (2)$$

In Equation 2, $D_{overprint}$ is the density of the two-colour overprint, $D_{first\ colour}$ is the density of the first colour printed, and $D_{second\ colour}$ is the density of the second colour printed. Several workers [e.g., 17] have suggested modifications to or variations on Preucil's equation. However, the original Equation 2 is still the most commonly used. The usual convention states that the complementary wavelength for the second colour printed is used to measure the densities (440 nm to measure yellow, 540 nm for magenta and 620 nm for cyan). As discussed below, this choice of wavelength is a serious shortcoming of Preucil's equation.

Results and discussion

Subjective ranking: 150 lines per inch, 100 lpi, and stochastic images

Subjective rankings were carried out on test images printed at different screenings. The Musicians image was printed and ranked separately at 150 lines per inch (lpi), 100 lpi, and with stochastic screening. The Candlesticks image was also printed and ranked at 150 lpi, for both top and bottom sides. As shown in Table II, in all cases, the top to bottom correlation is poor to non-existent. In all cases, the same-side correlations for the same image range from good to excellent.

The poor top-to-bottom correlations are due in part to two-sidedness in the sheet structure. Furthermore, correlations between bottom side rankings and measurements of bottom side properties (printed and unprinted) tended to be poorer, as discussed below.

Differences between the same-side correlations of the different prints — for example, between the stochastic Musicians print and the 150 line per inch print — are genuine, due to the inability of some of the papers to properly reproduce the smallest dots, as follows.

Figure 3 shows micrographs of halftone areas from three samples: a well-ranked SCA (sample 48) , a moderately-ranked MF grade (sample 34) , and a poorly-ranked newsprint (sample 37). These micrographs show 50% halftone coverage areas (i.e., the paper is nominally 50% covered by ink and 50% blank) for the 100 lpi region, the 150 lpi region, and the stochastic region.

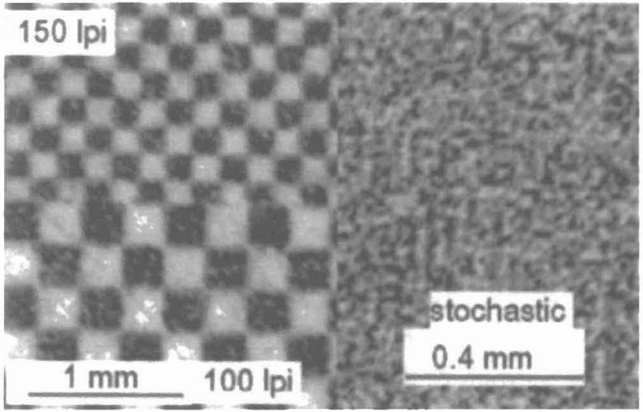
For the SCA sample, the 100 lpi and 150 lpi dots are about equal in quality. As we go to the lower ranked MF sample and the still-lower ranked newsprint we see that the finer 150 lpi dots become increasingly degraded, to the point of being almost entirely obscured. The stochastic dots are of particular interest. These images are indeed in focus, so that we can see significant degradation of the stochastic dot structure even for the SCA sample. For the MF sample, the dots are much degraded, while for the newsprint, the dots are completely smeared and are not resolved.

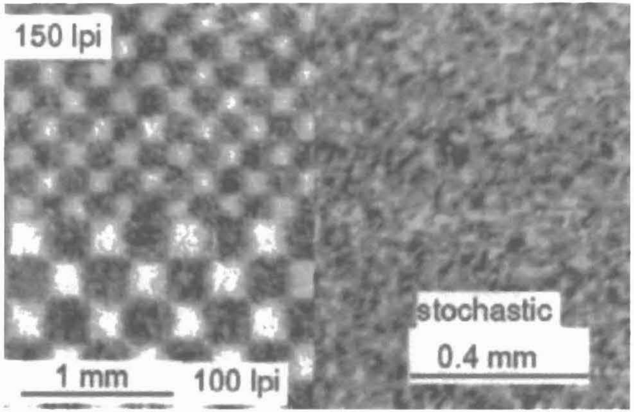
The nominal 50% dot diameter at 100 lpi is about 250 μm, while the dot diameter at 150 lpi is about 170 μm. However, the stochastic dot diameter is only 21 μm. Differences in ranking between (e.g.) stochastic and other types of printing are due largely to the way in which different sheet structures interact with halftone dots of different size. The smallest dots are the most difficult to reproduce correctly on a rougher, coarser paper surface, placing such surfaces at a disadvantage. The difference between the top side ranking of the 150 lpi and stochastic Musicians correlated with the optical spreading of the dots and the stochastic dot diameter, with $R^2 = 0.55$. That is, 55% of the difference between the stochastic and conventional screening on the same paper can be explained by differences in their optical and physical dot spreading. The optical spreading was determined from laser xerographic prints, as described above and in a separate publication, [18], while the stochastic dot size was measured using the Paprican Inkscanner [15].

Subjective ranking, paper, and print properties

Tables III and IV show, respectively, the top and bottom side correlations among the subjective ranking and various physical and optical properties of the paper and the Musicians photograph.

Figures 4 shows the top side rank vs. the Print Surf roughness, with $R^2 = 0.64$ (top side). The correlation between rank and the Print Surf roughness of the bottom side of the paper is 0.09. While the poor bottom side Print Surf correlation may appear surprising, sufficient data can be found in the literature to show that Print Surf measurements must be treated with caution when comparing samples from a wide range of paper machines in offset printing [e.g., 1, 19, 20].





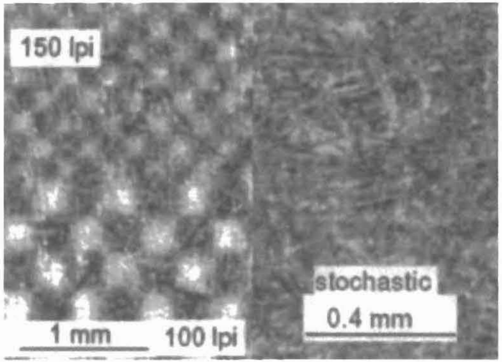


Figure 3. Micrographs of dot areas. Upper left: SCA sample 48. Upper right: MF sample 35. Bottom: newsprint sample 37. Each image contains a 150 line per inch, 100 lpi and stochastic image. Note that the dot quality becomes much poorer from the SCA to the MF to the newsprint, especially for the finer dots (150 lpi and stochastic). Scales are approximate.

TABLE I, Part 1, Key paper properties

Code	Grade	Comments	Rank - 150 lpi Musicians		Print Surf, S-10 μm		Gloss, %		Surface fibre length, mm		Formation index	Ash, %
			Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom		
31	SCA	High tack ink	11.7	20.5	1.27	1.32	38.8	40.0	26	33	167	25.7
32	SCA	High tack ink	12.8	11.2	1.44	1.57	41.5	38.0	17	15	223	27.9
33	SCA	High tack ink	15.3	5.6	1.61	1.69	36.2	25.2	28	10	180	19.8
34	MF		37.7	31.8	2.87	2.81	14.4	13.9	105	69	161	10.5
35	MF	Same machine as # 36	25.7	36.7	2.84	2.96	13.6	13.0	106	92	160	12.0
36	MF	Same machine as # 35	33.2	23.8	4.03	4.05	9.1	7.9	129	102	106	5.9
37	NEWS		40.4	52.6	4.00	3.92	11.8	10.3	109	112	137	1.2
38	SOFT		36.2	58.7	2.60	2.13	17.4	20.0	87	55	108	0.6
39	SOFT	Same machine as # 40	16.8	25.4	2.60	2.43	20.1	22.2	59	31	143	4.3
40	SOFT	Same machine as # 39	12.4	12.1	2.47	2.53	23.0	18.8	53	32	170	9.2
41	SCA	Identical to #32	7.2	13.2	1.44	1.57	41.5	38.0	17	15	223	27.9
42	SCB		27.3	51.2	1.74	1.65	27.4	27.6	69	46	114	0.3

NOTES: Samples 31–33: High tack ink; Samples 34–60: Low tack ink.
SCA, SCB, and SCC: supercalendered. Soft: soft-calendered. MF: Machine finished. News: newsprint

TABLE 1, Part II Key paper properties

Code	Grade	Comments	Rank - 150 lpi Musicians		Print Surf, S-10 µm		Gloss, %		Surface fibre length, mm		Formation index	Ash, %
			Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom		
43	SCA	Identical to # 33	15.3	5.6	1.61	1.88	36.2	25.2	28	10	180	19.8
44	SCC		19.5	45.1	1.74	3.22	24.5	29.5	53	86	101	0.5
45	NEWS		46.7	26.8	3.63	3.34	10.7	9.3	201	103	136	0.5
46	NEWS		37.3	31.6	3.79	3.34	10.9	9.6	189	93	140	0.6
47	SCB	Repeat of #42	38.9	56.5	1.74	1.65	27.4	27.6	69	46	114	0.3
48	SCA	Identical to #31	7.1	35.9	1.27	1.32	38.8	40.0	26	33	167	25.7
49	SOFT	Repeat of #38	29.9	49.8	2.60	2.13	17.4	20.0	87	55	108	0.6
50	SCC		17.1	23.4	2.06	2.04	26.3	23.0	45	22	149	8.2
51	SOFT		18.6	49.1	2.24	2.44	25.7	22.8	52	71	114	0.2
53	NEWS		58.0	47.5	3.57	3.65	12.0	10.2	194	139	102	0.6
54	NEWS		53.4	44.0	3.56	3.89	11.5	9.7	194	183	108	0.5
55	NEWS		45.9	52.0	3.94	4.25	11.0	9.1	164	144	125	0.4
56	SCC		23.2	44.3	2.00	1.94	20.1	24.2	47	54	118	2.3
57	SCC		34.2	46.3	2.61	2.53	17.3	16.6	119	83	92	1.2
58	SCB		21.8	56.4	1.94	1.95	25.1	26.5	56	43	136	8.4
59	SCC		43.7	53.6	3.70	3.50	11.6	10.8	193	98	136	5.5
60	MF		40.0	63.5	2.66	2.66	16.3	15.6	84	93	126	0.3

NOTES: Samples 31–33: High tack ink; Samples 34–60: Low tack ink
SCA, SCB, and SCC: supercalendered. Soft: soft-calendered. MF: Machine finished. News: newsprint

TABLE II: Correlations between different prints, on top and bottom sides

Image	*Musicians 150 lpi top*	*Musicians 150 lpi bottom*	*Musicians 100 lpi top*	*Musicians 100 lpi bottom*	*Musicians stochastic top*	*Musicians stochastic bottom*	*Candlesticks 150 lpi top*	*Candlesticks 150 lpi bottom*
Musicians 150 lpi top	*1.00*							
Musicians 150 lpi bottom	*0.34*	*1.00*						
Musicians 100 lpi top	*0.84*	*0.23*	*1.00*					
Musicians 100 lpi bottom	*0.38*	*0.92*	*0.35*	*1.00*				
Musicians stochastic top	*0.80*	*0.17*	*0.72*	*0.18*	*1.00*			
Musicians stochastic bottom	*0.37*	*0.66*	*0.34*	*0.66*	*0.30*	*1.00*		
Candlesticks 150 lpi top	*0.84*	*0.16*	*0.81*	*0.20*	*0.82*	*0.26*	*1.00*	
Candlesticks 150 lpi bottom	*0.50*	*0.82*	*0.35*	*0.80*	*0.34*	*0.70*	*0.31*	*1.00*

TABLE III Correlations, top side

	Rank	Print Surf roughness	Compress-ibility	Formation index	Contrast intensity	Surface fibre length		Gloss		1/Gloss	
						Dry	After wetting	Dry	After wetting	Dry	After wetting
Rank	1.00										
Print Surf roughness	0.64	1.00									
Print Surf compressibility	0.68	0.73	1.00								
Formation index	0.38	0.20	0.28	1.00							
Contrast intensity	0.43	0.38	0.43	0.61	1.00						
Surface fibre length	0.80	0.79	0.70	0.25	0.45	1.00					
Surface fibre length after wetting & drying	0.84	0.69	0.63	0.44	0.55	0.90	1.00				
Unprinted gloss	0.67	0.84	0.78	0.44	0.48	0.72	0.73	1.00			
Gloss after wetting	0.70	0.71	0.75	0.56	0.51	0.67	0.78	0.93	1.00		
1/Gloss	0.66	0.94	0.67	0.17	0.41	0.79	0.73	0.85	0.76	1.00	
1/(Gloss after wetting)	0.79	0.84	0.76	0.29	0.48	0.85	0.86	0.84	0.94	0.82	1.00

TABLE IV Correlations, bottom side

	Rank	Print Surf	Compress-ibility	Formation index	Contrast intensity	Surface fibre length		Gloss		1/(Gloss)	
						Dry	After wetting	Dry	After wetting	Dry	After wetting
Rank	1.00										
Print Surf roughness	0.09	1.00									
Print Surf compressibility	0.20	0.50	1.00								
Formation index, unprinted	0.48	0.19	0.12	1.00							
Contrast intensity, unprinted	0.14	0.34	0.34	0.57	1.00						
Surface fibre length	0.25	0.77	0.70	0.33	0.48	1.00					
Surface fibre length (after wetting and drying)	0.50	0.58	0.63	0.51	0.44	0.86	1.00				
Unprinted gloss	0.09	0.73	0.78	0.18	0.37	0.57	0.39	1.00			
Gloss after wetting	0.16	0.65	0.60	0.27	0.42	0.58	0.51	0.90	1		
1/(Gloss)	0.03	0.82	0.54	0.11	0.39	0.65	0.41	0.84	0.73	1	
1/(Gloss after wetting)	0.06	0.76	0.56	0.16	0.45	0.72	0.53	0.82	0.83	0.93	1

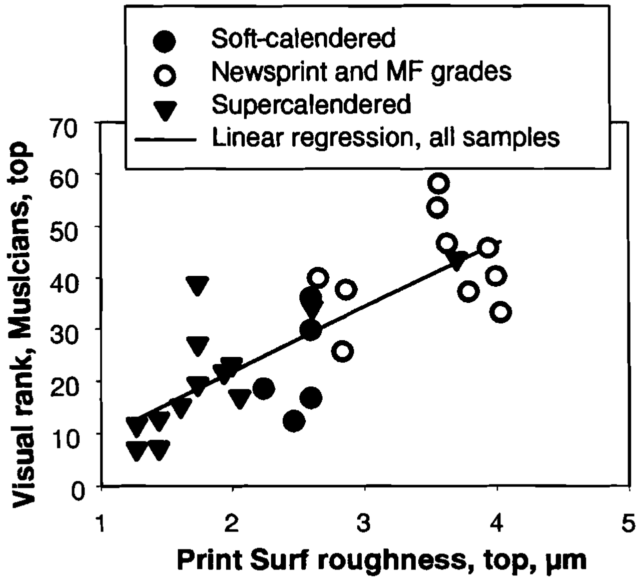


Figure 4. Top side visual rank (150 line per inch Musicians image) vs. Print Surf roughness. $R^2 = 0.64$.

Other correlations between ranking and properties related to surface quality or roughness were better, for the top side. For example, the correlation between the top side ranking and unprinted paper gloss was $R^2 = 0.67$ (Figure 5A). The correlation was even better between top side ranking and the gloss of paper that had been wetted and dried (to simulate the application of offset fountain solution to the non-image area: $R^2 = 0.70$, Figure 5B). Table III also shows that the correlation with the *inverse* gloss after wetting is better still ($R^2 = 0.79$).

However, the correlations were poorer on the bottom side: $R^2 = 0.09$ (gloss) and $R^2 = 0.16$ (gloss after wetting). We have no explanation for the much poorer correlations on the bottom side compared to the top. We note that when the same samples were printed by gravure, all on the same side of the press, the bottom side correlations were still poorer. Therefore, this is an inherent paper structural problem, which should be addressed in future work. Press sidedness effects are another, additional possibility, but were not explored in this work.

Exposed fibre length on the paper surface ("speed bumps") [10,11] — another property related to gloss and surface roughness — also provided an excellent correlation with subjective ranking of the top side prints: $R^2 = 0.80$ (dry paper, Figure 6A) and $R^2 = 0.84$ (paper after wetting and drying, Figure 8B). On the bottom side, correlations were respectively, 0.25 and 0.50.

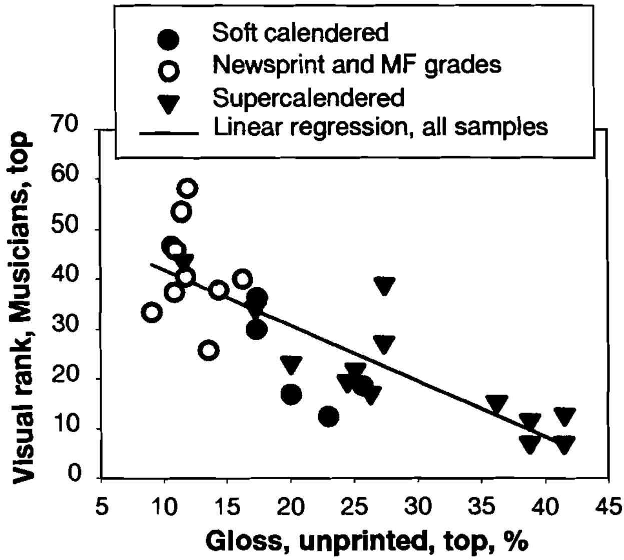


Figure 5A. Visual rank of top side prints vs. unprinted gloss. $R^2 = 0.67$.

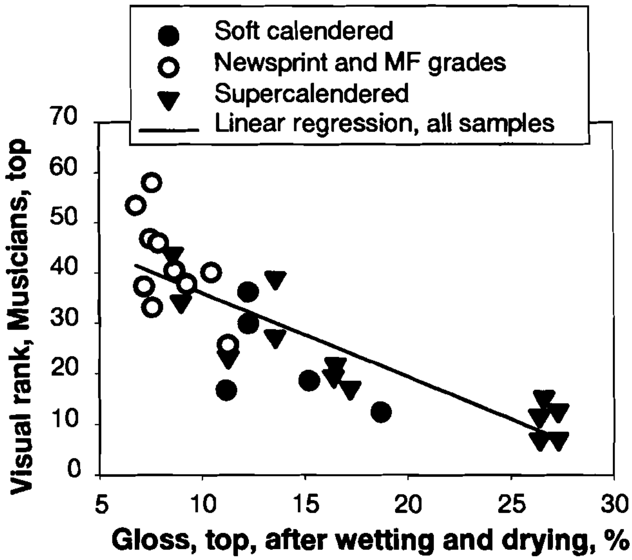


Figure 5B Visual rank of top side prints vs. unprinted paper gloss after wetting and drying. $R^2 = 0.70$.

The soft-calendered samples described in Table I and in this discussion have virtually identical Print Surf roughness — yet their subjective ranks cover a wide range. Gloss and (especially) exposed surface fibre length provide a much more sensitive discrimination among these samples, at least on the top side. In the bottom side figures, since correlations are much poorer, it is difficult to see any improved discrimination.

We also found a significant correlation ($R^2 = 0.68$) with compressibility measured using Bristow's approach [10], but a much poorer correlation with the bottom side Finally, the ranking ($R^2 = 0.20$) measured by image analysis (formation index) was significant ($R^2 = 0.38$ top side, and $R^2 = 0.48$, bottom side).

Subjective ranking and ink trapping

Especially in high speed multi-colour web offset printing, where one wet ink film is printed on top of other, still-wet ink films, trapping has always considered to be an important visual and physical property.

We found good correlations between subjective ranking and some ink trapping properties. For example, $R^2 = 0.63$ between subjective ranking and yellow on black trapping (top side), with better trapping indicating a better rank. The same trapping values correlated very well with sheet gloss ($R^2 = 0.81$). Bottom side rankings were poorer but still significant ($R^2 = 0.32$ — trapping vs. ranking, $R^2 = 0.46$ — trapping vs. gloss). Correlations were also good with magenta-on-black trapping. The correlations with gloss are an indication of the contribution of surface structure to uniform ink transfer.

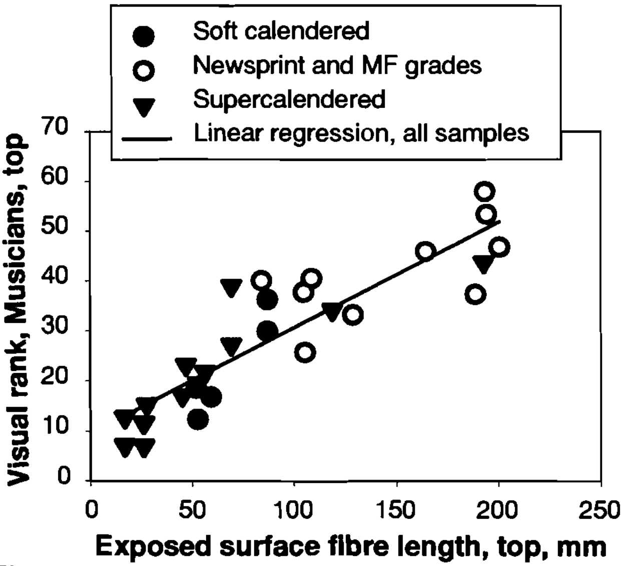


Figure 6A Visual rank of top side prints vs. length of exposed surface fibres. $R^2 = 0.80$.

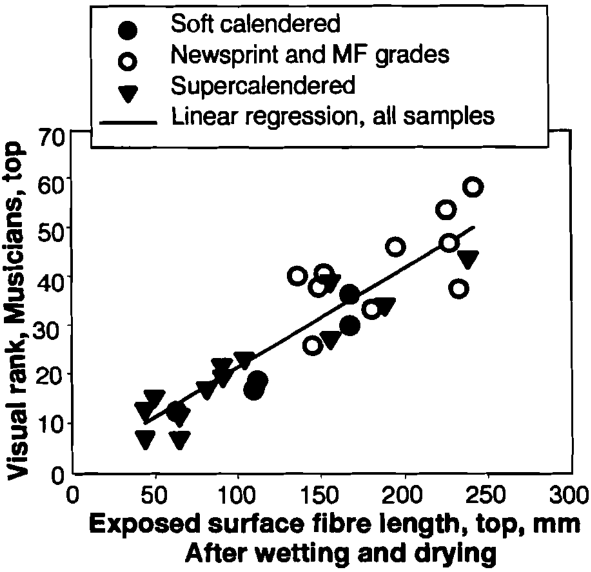


Figure 6B Visual rank of top side prints vs. Exposed surface fibre length after wetting and drying. $R^2 = 0.84$.

Implicit in any discussion of ink trapping is that colour fidelity is closely related to trapping. We therefore assumed that the best-ranked sample had the best colour fidelity, and that all other samples deviated from that ideal. We can therefore calculate colour differences from the measured colour coordinates of the trapping target area:

$$\Delta E^* = \sqrt{(L_O^* - L_i^*)^2 + (a_O^* - a_i^*)^2 + (b_O^* - b_i^*)^2} \quad (3)$$

where L_O^*, a_O^*, and b_O^* are the colour coordinates of the best print and L_i^*, a_i^*, b_i^* are the colour coordinates of any another sample i.

As shown in Figure 7, the correlation between subjective ranking and the colour shift between the best sample and the others is excellent ($R^2 = 0.85$). That is, poorer prints are those in which the colour is different from — one might say less faithful to — the reference print. The correlation between bottom side ranking and this colour shift were poorer, although still (barely) significant ($R^2 = 0.21$).Although the yellow on black correlations ranged from significant to excellent, correlations with one process colour onto another (i.e., yellow on magenta, magenta on cyan) were non-existent. Choosing 440 nm to measure yellow on cyan trapping maximizes the yellow density, but minimizes the cyan density. Naturally, when black is the first colour down, this wavelength dependency is not a serious problem. This should be the object of further study. It is likely that the correlations between subjective ranking and trapping are a sign of surface uniformity, as these also correlate with as gloss and surface fibre length.

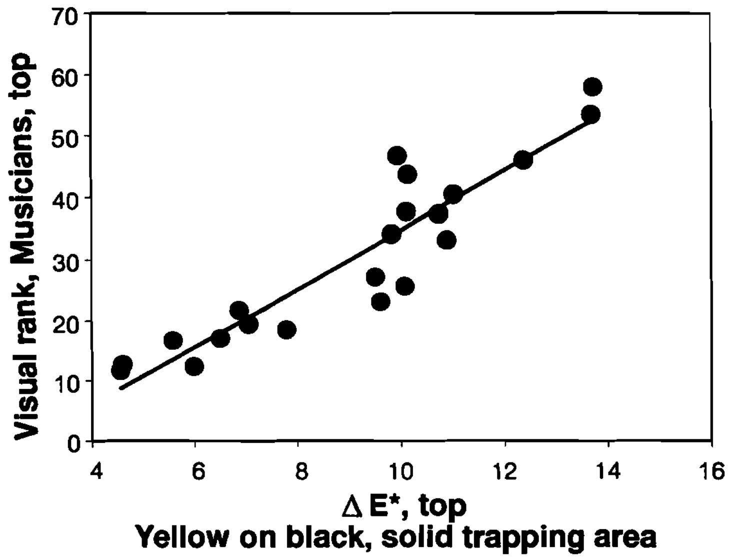


Figure 7. Colour difference between best print and other prints, as a function of top side subjective ranking. R^2 =0.85.

Microscopic examination of the paper surface under the ink

As discussed in our report on woodfree fine papers [5], pits up to 6 μm or so in depth can be "bottomed" by the printing blanket, leading to at least some ink transfer. Pores deeper than about 6 μm are not contacted by ink, and so blank areas are visible in the dot. In the present work, the influence of topography on dot quality and structure is even more evident for this wide range of samples. Figure 8 shows confocal and optical images for typical "good" and "bad" halftone dots printed on three samples: SCA (Sample 48), soft-calendered (Sample 40), and newsprint (Sample 37). The nominal dot diameter is approximately 50 μm. In the optical images, the halftone dots are supposed to be perfect, black disks, but we see that this is rarely the case. The 3-d confocal images are colour coded by depth, so the brightest areas are closest to the surface, and the darkest areas are deeper inside. The point "A" represents the reference plane, and depths are measured from this point. The nominal printed area is superimposed on the confocal image.

Figure 8A shows the SCA Sample 48. The ink coverage on the "good" dot is indeed uniform in the optical image. The corresponding confocal image is also uniform with no pits, and the deepest indentation of only about 2.3 μm — easily reached by the ink. The "bad" SCA dot in Figure 8B has one pit of up to 15 μm in depth. Relative to the dots on the poorly-ranked samples, this "bad" SCA dot is still of reasonable quality.

Figure 8C shows a good dot on the soft-calendered Sample 40, containing 9.24% ash. This dot is still reasonably uniform, showing relatively few pits in its surface. Finally, Figure 8D shows a bad dot on newsprint Sample 37. The "bad" dot is especially uneven, with a massive pit 20 μm in depth, taking up most of the dot's centre, and a large, coarse fibre which also contributes to image deterioration.

From these confocal images (10 dots per sample) we obtained the distribution of the pore areas as a function of pore depth. Table V summarizes the widths of the pore depth distributions. Areas of "bad dots" and areas of "good dots" (in the opinion of the operator) were chosen. The operator also chose random areas of 4.7 mm^2 to represent the paper surface as a whole. Table V shows that the broadening of the pore depth distribution as we go from "good" to "bad" dots, with the SCA sample being having the most uniform surface and the newsprint the least uniform. Figure 9 shows the area/depth of penetration curves for different halftone dots, showing the variation from grade to grade and from "good" to "bad".

TABLE V : Width of pore depth distribution curves at half maximum, μm

	Newsprint Sample 37	*Soft calendered Sample 40*	*SCA Sample 48*
Random areas (4.7 mm^2)	*9.5*	*6.8*	*5*
"Bad" dots	*12.4*	*12.8*	*4.4*
"Good" dots	*11.2*	*5.7*	*3.9*

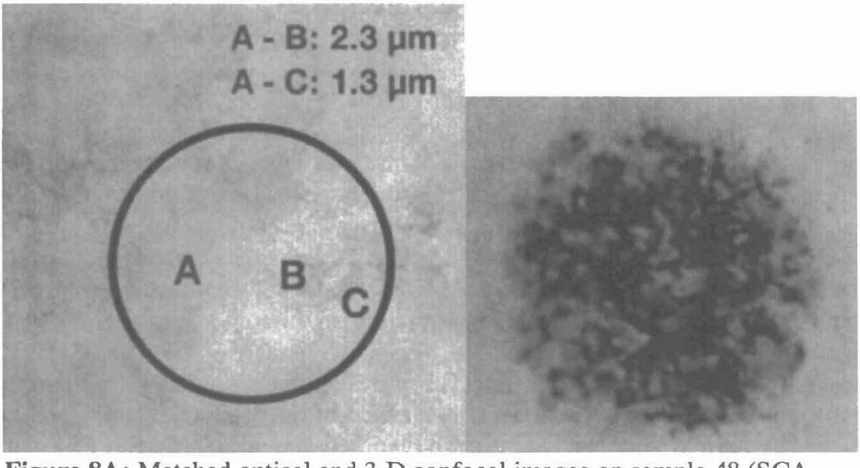


Figure 8A: Matched optical and 3-D confocal images on sample 48 (SCA, excellent score). In the confocal image, the darker the area, the deeper it is from the reference plane. Depths are given from the reference point A.

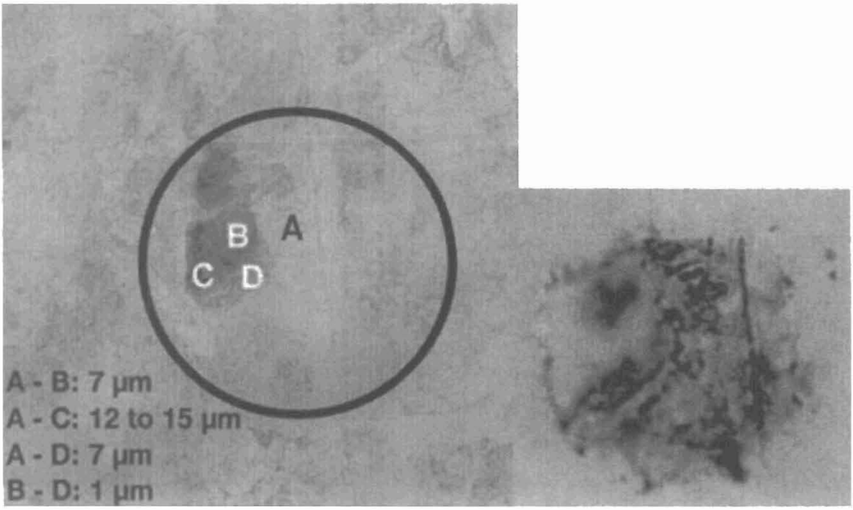


Figure 8B. SCA sample 48, excellent score: a "bad" dot.

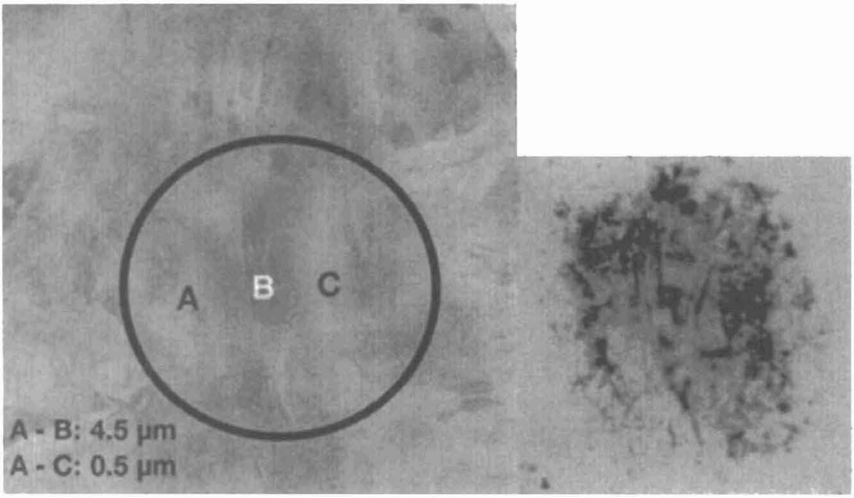


Figure 8C Matched optical and 3-D confocal images on sample 40, a soft-calendered sample with an intermediate score. A "good" dot.

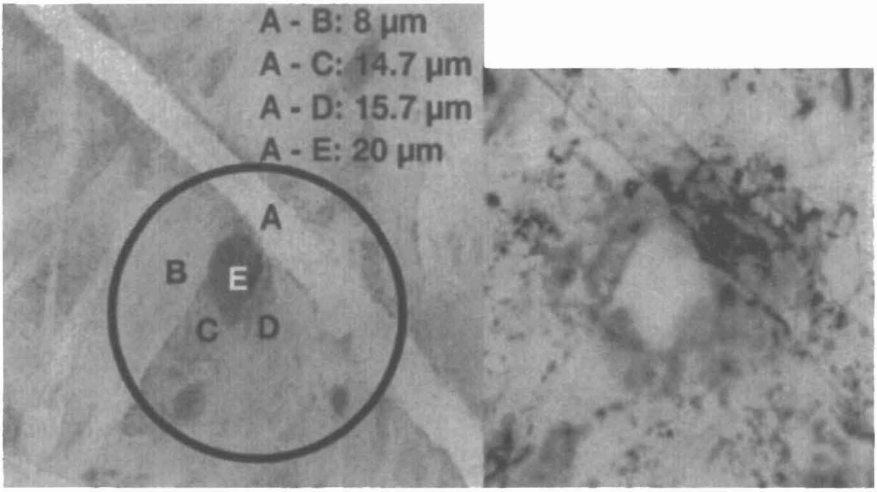


Figure 8D. Matched optical and 3-D confocal images on sample 8D, a newsprint sample with a poor score. A "bad" dot.

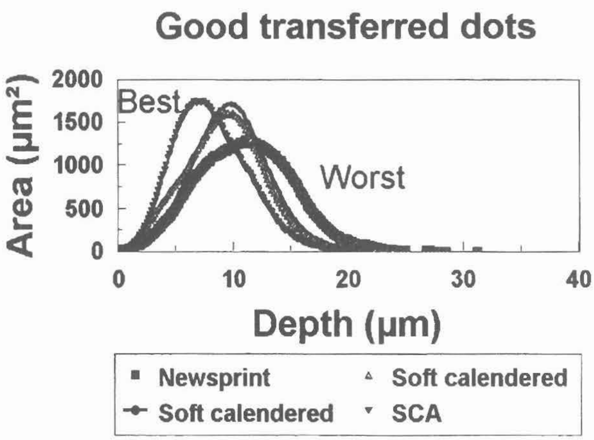


Figure 9A: Distribution of internal pore area and depth for "good" halftone dots.

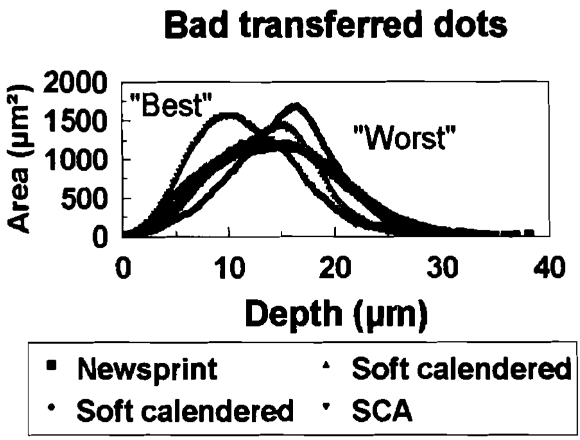


Figure 9B: Internal pore area and depth for "bad"halftone dots. Compare these much broader distributions to the "good" dots of Figure 9A.

Conclusions and implications for the papermaker

Among the paper surface factors examined, the total length of fibre exposed on the paper surface, or the "speed bumps", gave the highest correlation with the subjective ranking. This may provide a useful quality control tool. The correlation between the subjective judgements and the unprinted paper gloss was also meaningful, at least on the top side of the sheet, but poor on the bottom side of the sheet. The same was seen for Print Surf roughness. Compressibility of the sheet may be another important issue.

In general, correlations between ranking and paper properties were much poorer on the bottom side of the sheet. We have no explanation for the much poorer correlations on the bottom side compared to the top. However, we note that when the same samples were printed by gravure, all on the same side of the press, the bottom side correlations were poorer. Therefore, this is an inherent paper structural problem, which should be addressed in future work.

Among print properties, only ink trapping gave a good or significant correlation with subjective judgements. In turn, the deviation in colour between the best print and all other prints also correlated very highly with subjective quality. Since ink trapping also correlated with unprinted paper gloss, this may be an indication of surface uniformity. Even here, the bottom side correlation rankings ranged from poor to non-existent.

Acknowledgements

The authors would like to thank the many mills who contributed samples to this trial. The RIT press crew was led by Dan Clark. The Paprican group who were present at the trial included Byron Jordan, Tony Manfred, Sylvie Sauriol, and Nancy Somerville. Print quality lab work was done by Josiane Chasle, Tony Manfred, Maureen O'Neill, Lorraine Perron, Sylvie Sauriol, and Nancy Somerville. Josiane Chasle did the measurements on the confocal microscope.

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