THE PRIMARY PAPER PROPERTY THAT AFFECTS DENSITY RANGE

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Abstract: A given ink, printed at a film thickness of one micron, on a wide range of stock, is known to produce solid ink densities (measured to the paper) ranging from a low of about 0.80 to a high of over 1.30 density units. This paper reports on the measurement of the properties of fifteen different substrates that were so printed and examines how well the various properties correlate with density range. In general, the properties studied can be categorized as relating to either the topographic, optical, or permeable characteristics of the papers. From the data obtained, it is concluded that the observed differences in density range are attributable to a single paper characteristic.

Background and Introduction

This paper is to report further on a project initially undertaken to explore the interaction of ink and paper properties (MacPhee and Lind, 1991). More specifically, it is aimed at disclosing the effect of paper properties on density range; defined as the difference between maximum (or solid) and minimum (or paper) density at a given ink film thickness printed by the lithographic process. The fifteen printed samples used in this work were all printed on a sheetfed press at a nominal ink film thickness of one micron, as described in a previous report (MacPhee and Lind, 1992). Figure 3 of that report is a plot showing that density range generally followed paper quality as measured by grade and finish. That is, the lower the paper quality, the lower the density range. The test print data in the 1992 reference that were used in this current work are reproduced in Table I. In this regard, it is to be noted that all of the solid densities in Table I have been corrected to an ink film thickness of 1.04 grams/m^2.

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Table I Test print data

Run No.	Paper properties				Print Properties				
	Grade/type	Brightness	Basis weight (pounds)	Calliper (inch)	Paper density	Solid density	Density range		Gain, 40% line screen (percent)
							Value	Rank	
1	#1 Ctd. offset	86.1	100	4.8	0.04	1.36	1.32	4	15.7
2	#5 Ctd. offset	77.3	60	3.0	0.09	1.33	1.24	8	18.4
3	#3 Ctd. offset	68.5	60	3.0	0.12	1.43	1.31	5	21.1
4	#5 Ctd. offset	68.6	60	3.2	0.12	1.37	1.25	7	19.1
5	#5 Ctd. offset	74.7	60	3.0	0.09	1.36	1.27	6	18.8
6	#1 Ctd. offset	86.9	60	5.2	0.05	1.39	1.34	1	17.4
7	#1 Unctd. offset	81.6	60	3.9	0.07	0.93	0.86	12	20.6
8	Uncalendered nwspr.	56.6	30	4.0	0.18	0.94	0.76	15	19.9
9	Calendered nwspr.	55.8	30	3.6	0.20	1.02	0.82	14	20.3
10	#3 Ctd. offset	86.5	100	4.3	0.05	1.38	1.33	2	18.3
11	#1 Unctd. offset	93.9	65	10.6	0.03	0.93	0.90	10	20.2
12	#1 Ctd. offset	88.3	(8 point)	9.0	0.04	1.37	1.33	3	14.3
13	Tyvek	94.8	(8 point)	5.0	0.03	0.90	0.87	11	21.8
14	#3 Ctd. gravure	70.9	60	3.3	0.11	1.33	1.22	9	15.1
15	#3 Unctd. offset	82.7	70	5.0	0.07	0.90	0.83	13	16.7

The main body of this paper is made up of four sections. The first discusses various mechanisms that could account for the observed differences in density range. These mechanisms are pertinent because they prompted the choice of specific paper properties that were measured. The second section presents the measured data and includes plots of density range versus various paper properties. The third section includes a discussion of what can be inferred from all of the data obtained and also describes some miscellaneous tests that were carried out to gain additional insight . The final section gives the authors' conclusions.

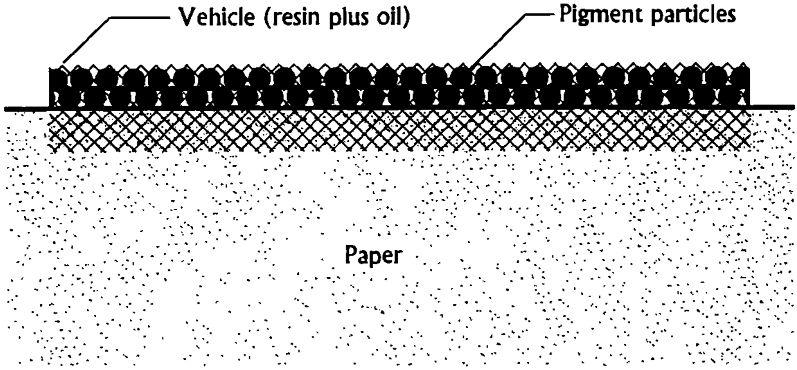
Mechanisms That Could Account for Density Range Variations

One theory put forth is that variations in ink film formation on paper are the reason for density range variations. In other words, if ink film formation were the same on all printed samples, density range would not vary. The soundness of this theory was demonstrated by measuring the density range of a film of colored plastic overlay, of the type used to make off-press proofs, placed on the two extremes of substrates used, a #1 coated sheet and uncalendered newsprint. The resultant measured density ranges differed little, as shown by the data in Table II. This infers that paper properties per se are not significant but rather are only important in how they influence ink film formation. Thus, it was considered important to examine how various paper properties affect film formation, as a prelude and guide to selecting those properties that should be measured.

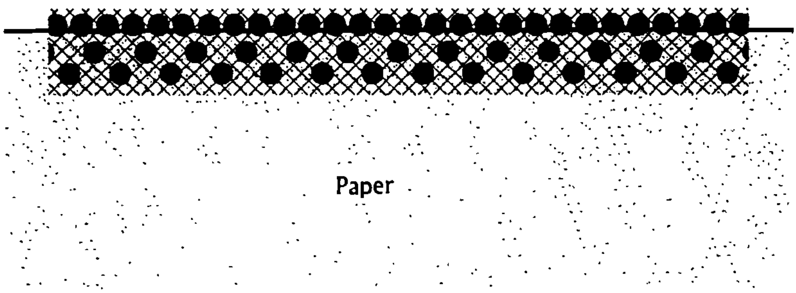
Table II Results of tests run to demonstrate that differences in density range can be due to differences in film formation. Here the same film overlay on two different papers was shown to produce almost the same density range, in contrast to an ink film. Overlays were laminated to papers to eliminate air interface.

Paper number	Density reading			Density range	
	Unprinted paper	Ink film on paper	Overlay on paper	Ink film on paper	Overlay on paper
1	0.04	1.36	1.54	1.32	1.50
8	0.18	0.94	1.58	0.76	1.40

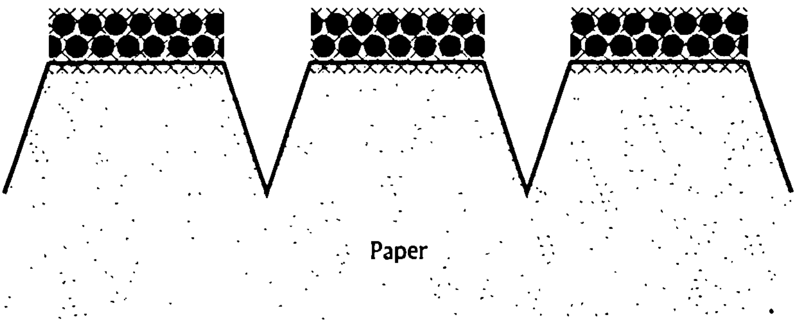
Figure 1 illustrates three different mechanisms of film formation that are generally thought to operate, depending on ink and paper properties. Figure 1(a) is a model of the film forming mechanism that is believed to predominate in films printed on coated paper (Aspler and Lepoutre, 1991). Here some of the oil in the vehicle is absorbed into the paper, leaving a mass of filtered pigment particles entrapped or immobilized in that



(a) Some of the oil in the vehicle migrates into the paper leaving a film of concentrated pigment on the surface of the paper.



(b) Both vehicle and pigment migrate into paper resulting in dispersion of pigment in paper.



(c) Transfer of ink film to paper is non-uniform due to presence of crevices in paper surface

Figure 1 Idealized models showing three different printed ink film formations on paper.

portion of the vehicle remaining on the surface. (In heatset lithographic printing, most of the ink oil is evaporated, producing the same result.) If this were the main mechanism for all samples , then one would speculate that the optical and/or permeable properties of paper would govern density range. This is because in such a case, the only significant difference between printed samples would be in the changes induced in the scattering properties of the paper beneath the ink, due either to differences in the depth of oil penetration or to differences in the optical properties of the oil-paper matrices.

Figure 1(b) is a model of the film forming mechanism that is thought by many to predominate in newspaper and book printing, i.e. on uncoated stock. Here, it is postulated that pigment is carried into the paper along with the high-oil-content vehicle, as it is absorbed. The basis for believing this mechanism to be operable is the conclusion reached in an early PATRA study (Coupe and Hsu, 1961) that ink penetrates porous paper as a homogeneous body, without filtration. In such a case, dispersion of pigment in the paper would reduce print density, compared to the situation where pigment is immobilized on the paper surface. If this were the dominant mechanism, it would follow that density range differences could be accounted for by differences in paper porosity or holdout.

The third film forming mechanism, shown in Figure 1(c), is planar in nature in that it results in film voids or uninked areas on the paper surface. These voids are caused by the presence of crevices or valleys in the paper surface that are large enough to prevent ink transfer. Such voids in actual printed samples can be readily detected with an optical microscope and it is obvious that surface topography is a function of their extent (size and frequency).

In addition to differences in ink film formation, there is another mechanism that can explain the observed differences in density range. This has to do with the fraction of the light sensed in a densitometer that is due to first surface reflection. It is more easily explained through the use of the simplified diagram given in Figure 2. For the case of a perfectly flat paper surface, a densitometer only sees or responds to light that is scattered by ink and/or paper particles that lie beneath the surface, i.e. the bulk scattered light, because such light is scattered in all directions. In contrast, all of the surface scattered or reflected light is reflected at a single angle that is equal to the corresponding angle of the incident rays. Densitometers are designed to be blind to surface reflected light and this is accomplished by placing the light source normal to the surface, and placing the detector at 45 degrees, as shown in Figure 2. (The same result is achieved by reversing the angles of light source and detector.) Thus none of the light rays reflected by a

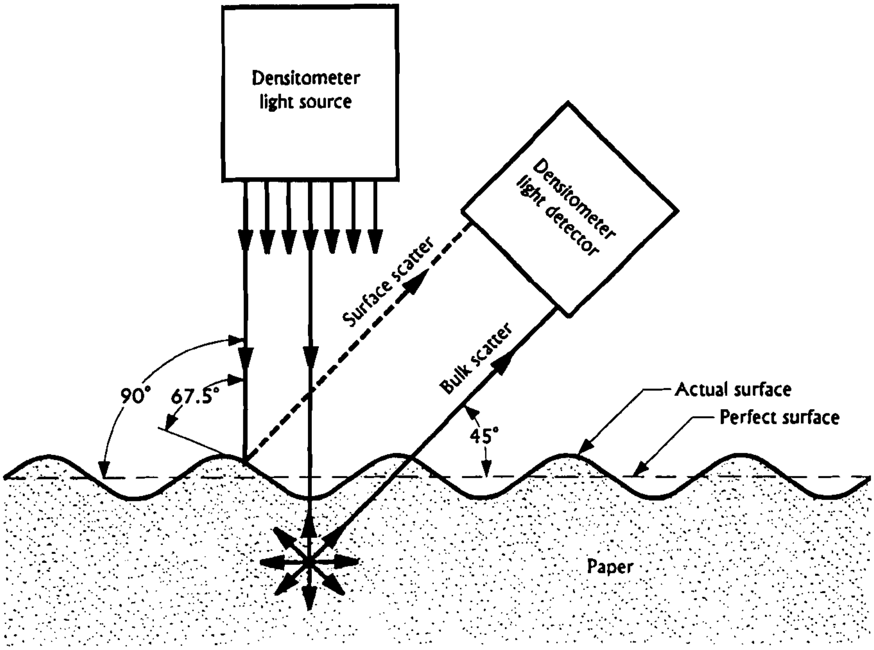


Figure 2 Simplified diagram of a densitometer. Ideally the sensor only responds to bulk scattered light. Light reflected by a perfect surface is directed back toward source. For an actual surface , some surface reflected light will be directed toward sensor, as indicated by dotted line.

perfectly flat surface will be directed toward the sensor. In actuality, all man-made surfaces exhibit some degree of roughness. In Figure 2, a surface having a sinusoidal contour is illustrated. In such a case, some portions of the surface will be at an angle of 67.5 degrees to the normal of the perfect surface and consequently will reflect light rays toward the detector. Thus the response of a reflection densitometer to paper samples with a rough surface will contain more surface reflected light than will the response to very smooth papers. The significance of this lies in the fact that an ink film only attenuates the bulk scattered light, thus a given film of ink on a very smooth paper will produce more attenuation in densitometer response than it will on a rough paper.

If this last mechanism is what governs it will be obvious that surface topography is the paramount paper property vis-à-vis density range. What will not be obvious is what feature of surface topography correlates best with density range. This is analogous to the problem of determining what printing plate topographic characteristics are most crucial to lithographic performance (Rouis and Goodman, 1993).

Data Obtained on Paper Properties

Thirteen different sets of properties of the papers used in making the test prints were measured in the course of this work. These measurements were divided into the three groups that will now be discussed: topographic, optical, and permeability.

Topographic Properties. Two different roughness measurements were made along with three different measurements of surface light scatter: gloss at 75 degrees, gloss at 60 degrees, and Bidirectional Scatter Distribution Function, or BSDF (Stover, 1990). The first set of roughness measurements were made using a mechanical profilometer equipped with a diamond stylus having a tip radius of 5 micron. The second set was made by the air leak method using the Parker Print-Surf (Parker, 1981). Although it might be argued that gloss is an optical property, gloss is grouped here because it is a well-known indicator of roughness (Zelley, 1972). The BSDF measurements were supplied by Kelley Kirchner of TMA Technologies in Bozeman Montana, and were made with a 633 nanometer wavelength laser beam placed at an angle of 75 degrees from normal. When the sample is reflecting, as in this case, the appropriate function is termed BRDF (for Bidirectional Reflectance Distribution Function) and is defined as in Equation (1):

$$\mathrm{BRDF} = \frac{Ps / \Omega}{Pi(\cos \theta s)} \qquad (1)$$

where:

Ps = scattered (reflected) power
Pi = incident beam power
θs = angle of detector from normal
Ω = scatter solid angle.

Before tabulating, the measured data was cosine corrected (multiplied by the cosine of the detector angle). Figure 3 is a plot of four sets of BRDF data, for two uncoated and two coated papers. The relative response of coated versus uncoated paper shown here is typical of all the samples measured.

Appendix A-1 is a tabulation of these five sets of topographic data. Figures 4 and 5 show plots of density range vs. the roughness data. Correlation is poor for the profilometer data and fair at best for the Parker

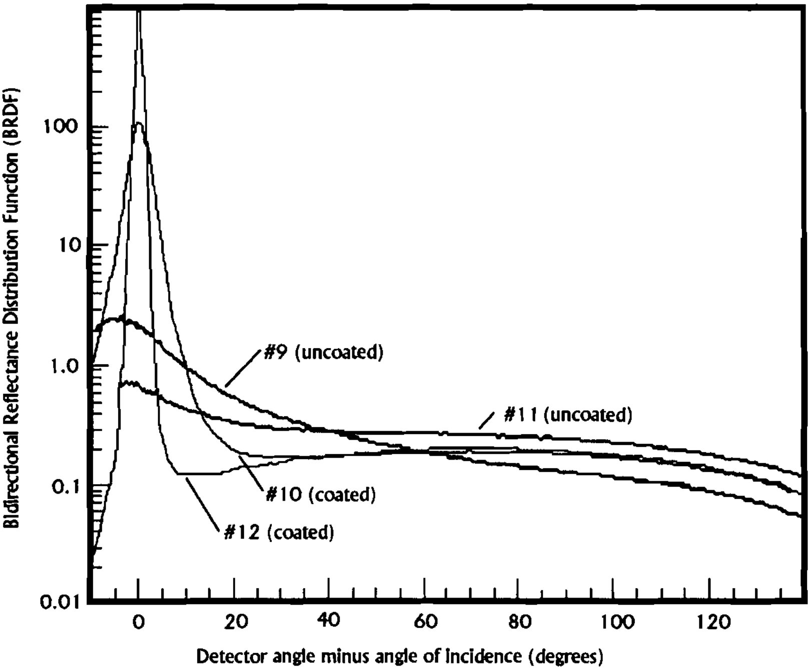


Figure 3 Four plots of cosine corrected data.

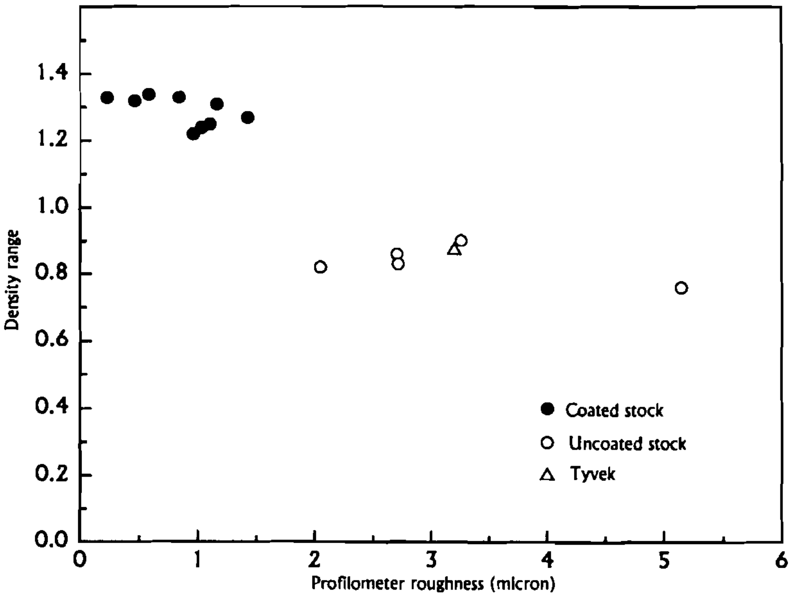


Figure 4 Density range versus profilometer roughness.

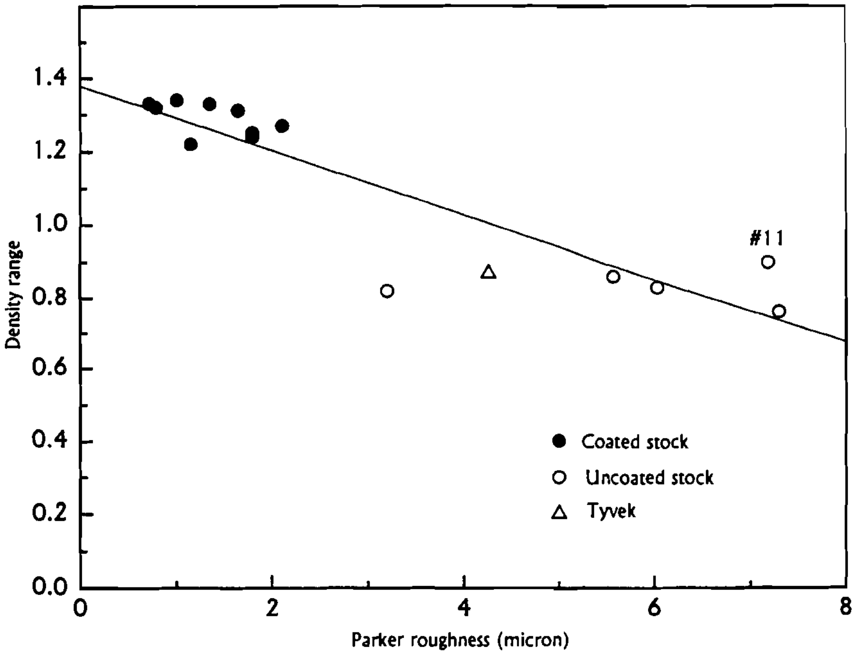


Figure 5 Density range versus Parker roughness.

roughness measurement. Better correlation is seen in the 60 degree gloss plot, given in Figure 6. (A plot of the 75 degree gloss data has not been included because it is about the same.) As for the BRDF data, the ratio of the response at a 45 degree angle difference (detector angle minus incident angle) to the maximum was selected after many trials by the authors as the best figure of merit. The rationale for using this ratio is that it incorporates both specular reflectance and the reflectance in the region where lack of smoothness produces a greater response. This angle also corresponds to the angle between the light source and the detector of a densitometer. The ratio BSDF data is plotted in Figure 7 and shows quite good correlation.

Optical Properties. In addition to TAPPI brightnes given in Table I, the following optical properties were measured: Ro, R_{∞}, fluorescence, and brightness directionality. From these measurements, values of printing opacity, scattering power, and absorbing power were calculated. Both the measurements and calculation were carried out by Patrick Robertsòn of Technidyne in accordance with Technidyne's established procedures (Popson, 1991). Except for brightness, these data are given in Appendix A-2. No plots of these data are given here because little or no correlation was found between density range and optical properties. It is anticipated,

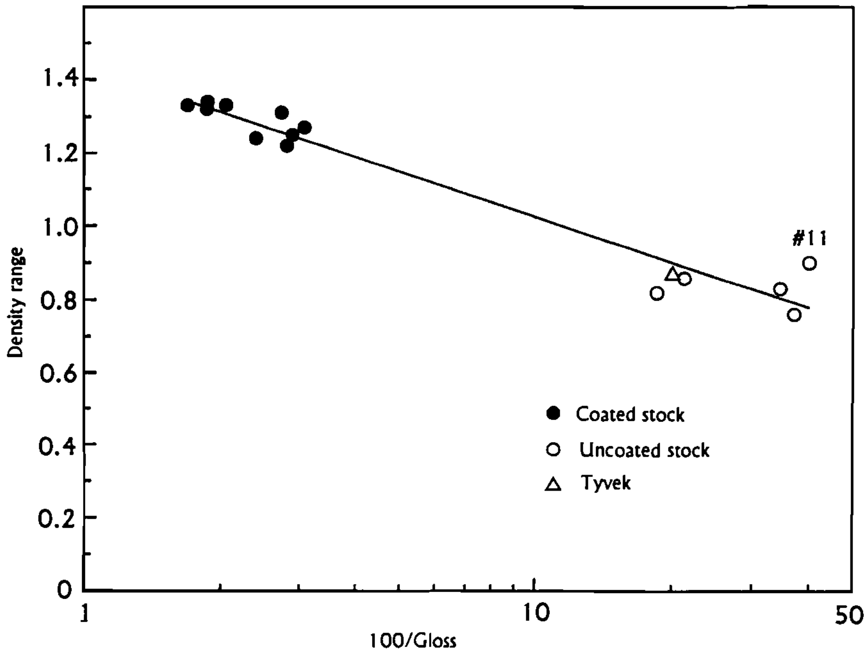


Figure 6 Density range versus gloss at 60 degrees.

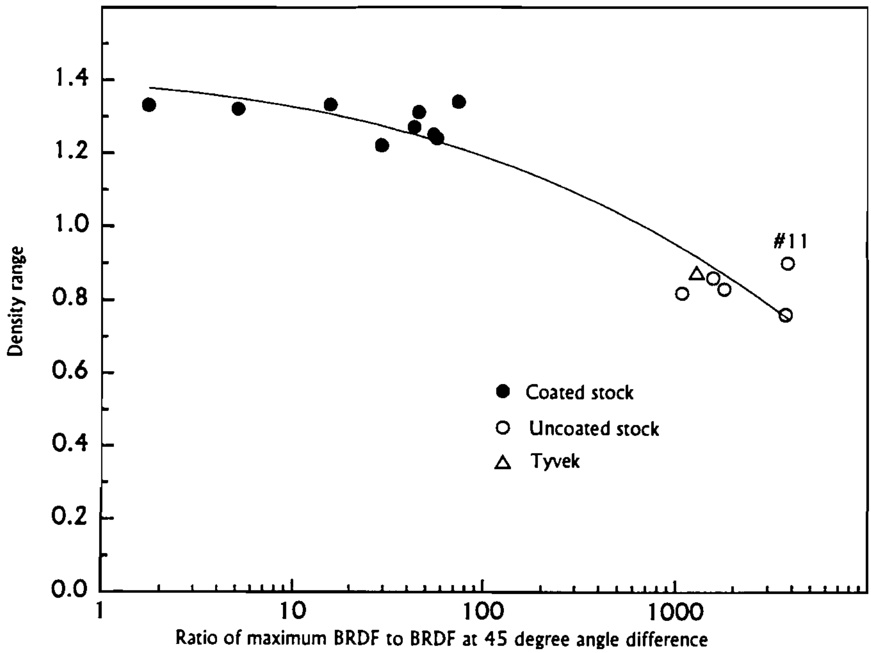


Figure 7 Density range versus BRDF ratios.

however, that this data will be helpful in future attempts to learn how the observed dot gains relate to paper properties.

Permeance. The last group of paper property measurements made relate to permeance or holdout, where holdout is defined as "the extent to which paper resists or retards the penetration of the freshly printed ink film" (Groff, 1991). Three different types of measurements were made: porosity to air, K and N density, and Croda Red density. The measurement of porosity to air is referred to hereinafter as Parker porosity because a Parker Print-Surf instrument was used. There was very poor correlation between density range and Parker porosity, as shown in Figure 8. The other two measurements exhibited much better correlation, as evidenced by the correlation coefficients for the two straight line fits to the data plotted in Figures 9 and 10.

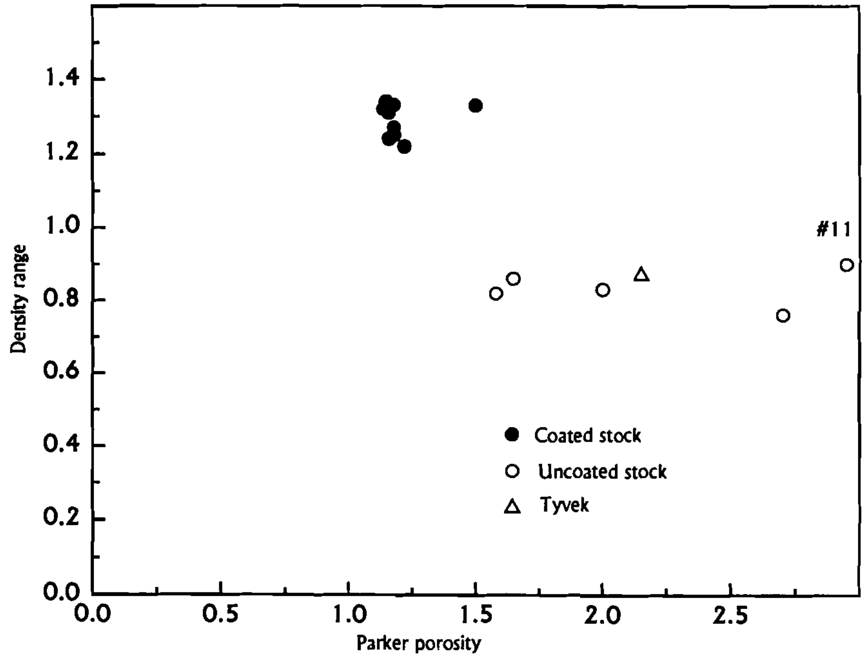


Figure 8 Density range versus Parker porosity.

Discussion

There is support for the hypothesis that a relationship exists between surface topography and density range, given the reasonable correlations with the gloss, BRDF, and Parker roughness measurements and the fact that such a relationship can be explained by either the mechanism illustrated in Figure 1(c) or the one in Figure 2. (The fact that the fourth set of topographic

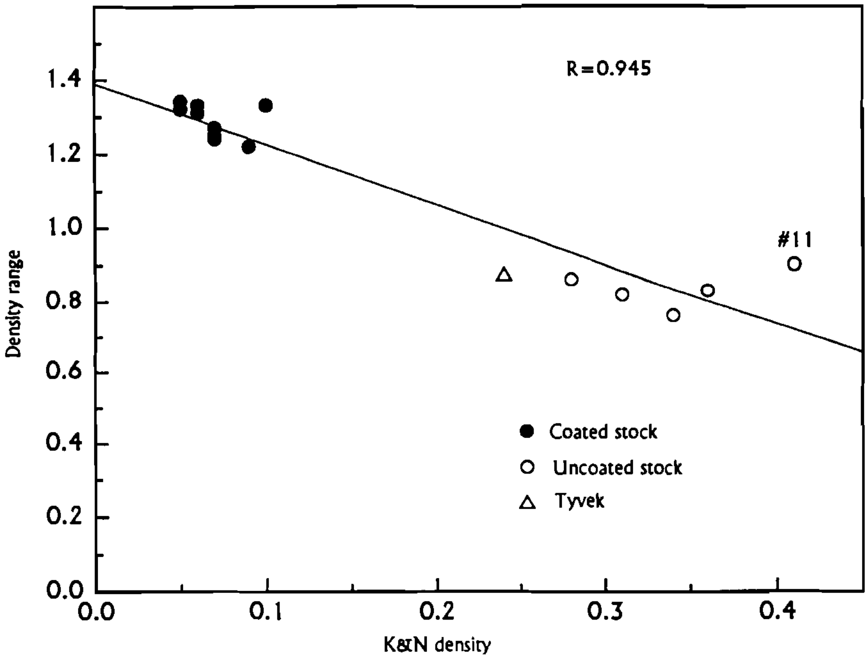


Figure 9 Density range versus K&N density.

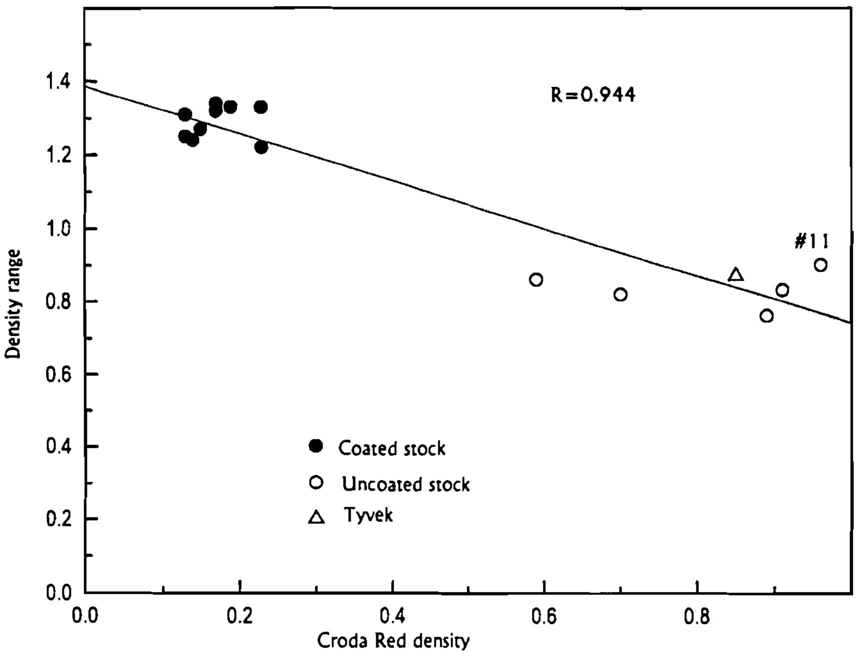


Figure 10 Density range versus Croda Red density.

measurements, the profilometer data, showed poor correlation may be due to the inability of the diamond stylus to accurately track the soft paper surface.) Visual examination of the prints led to the judgement that the mechanism of Figure 1(c) was not a significant factor, i.e. there were not enough voids in the film to account for the density differences.

Alternately it can be argued that there is support for supposing that a relationship exists between density range and the absorptivity of paper because two of the three sets of permeability measurements show a correlation. Here again, as shown in Figure 1(b), there is a theoretical basis for such a relationship to exist. There is, however, a very strong argument against this thesis because the two sets of measurements that correlate well, K&N and Croda Red density, are not direct measures of absorptivity, but rather simply mimic the printing process. Furthermore, the one set of measurements that directly reflect absorptivity, i.e. the Parker porosity measurements, correlate poorly with density range.

Further evidence was sought by carrying out an additional experiment. This involved making off-press prints on an IGT print tester, using the same ink as run on press. The paper used was a newsprint, comparable to #9 in Table I. The intent of this experiment was to seal the substrate with a coating, without changing surface roughness. It was reasoned that if the density range of a print made on a very absorbent given paper was little affected by sealing, then it could be concluded that paper absorptivity is not an important factor governing this print property. Sealing was accomplished by using a laboratory blade coater to apply both varnish to one set of unprinted samples and a water-based coating to a second set. Coated and uncoated samples were then printed on the IGT print tester and curves of density vs. ink film thickness were plotted for each of the three sets of samples. These curves were used to obtain the print densities corresponding to the reference ink film thickness of 1.04 gms/m^2. Roughness measurements were also made on unprinted samples, using the mechanical profilometer, as were measures of absorptivity. The purpose of the former measurements was to confirm that the coating had not produced a smoother surface. The latter measurements involved placing a drop of water on an unprinted sample and measuring the time required for the water to be absorbed into the paper. This was done to confirm that the surface had indeed been sealed. The results of these measurements, given in Table III, offer convincing proof that paper absorptivity (to the ink used) had no significant effect on the density range of the prints that were the subject of this paper.

There are two other pieces of evidence that support the mechanism of Figure 2. The first comes from the BRDF measurements. In every case, the uncoated samples exhibited a higher response than did the coated samples, in the region of angle differences from about 15 degrees to at least 60 degrees. This greater response, which can be seen in figure 3, can only be attributed to higher surface reflectances of the uncoated papers at these angles. The second piece of evidence comes from the behavior of the curves of print density versus ink film thickness for the various papers. It is well known that such curves generally reach an asymptotic value of around 2.0 density units in the case of coated papers versus around 1.25 for uncoated stocks. It is difficult to imagine how the curves for uncoated papers could level off at such relatively low densities if the density limit was caused by pigment migration into the paper. Conversely, the lower asymptotic values are quite consistent with the mechanism of surface reflection.

One aspect of the data plotted in Figures 5 through 10 deserves brief mention. In every one of these plots, the point for paper #11 is an outlier. It is thought that the explanation for this is that paper #11 has a high degree of fluorescence and that this results in an artificially high density for the unprinted paper.

Table III Measurements made on IGT prints to determine the effect of sealing on density range at an ink film thickness of 1.04 gm/m^2. Stock used was newsprint similar to paper #9.

Sample number	Type of coating	Measurements before printing		Density range
		Roughness (micron)	Absorption time	
1	none	2.8	7 seconds	0.77
2	varnish	2.0	65 seconds	0.71
3	wtr. base	3.0	No absorption	0.80

Finally, the reader is reminded that a low tack quick setting sheetfed ink was used throughout (tack of 12 @ 1200 rpm, yield of 4200 dynes/cm, and Laray viscosity of 210 Poise). It is quite possible that different results would have been obtained if a more fluid ink, such as used in newspaper printing, had been used.

Conclusions

Considering all of the measurements and calculations presented here, the authors came to the following conclusions:

1. Surface topography is the single most important paper property that affects print density range, at least for the type of sheetfed ink used in this project. This conclusion is based on four items of evidence: the data

collected and plotted in Figures 4 through 10; the experimental results reported in Table III; the greater BRDF response exhibited by all of the uncoated paper samples beyond the specular angle, relative to the coated samples; and the low asymptotic values of the density versus ink film thickness curves for the uncoated stocks.

2. BRDF (Bidirectional Reflectance Distribution Function) measurements provided the best correlation and show the most promise as a method for characterizing the aspects of paper surface topology that influence density range. It would be especially interesting to repeat the BRDF measurements using a geometry similar to that of a densitometer, i.e. at an incident angle of 45 degrees.

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Appendix A-I Topographic properties

Run No.	Test print data			Topographic property data					
	Paper grade/type	Density range		Roughness (microns)		Gloss		BRDF	
		Value	Rank	Profilometer	Parker	75 deg.	60 deg.	Maximum	45 deg.
1	#1 Ctd. offset	1.32	4	0.47	0.79	68.3	53.5	341.7	0.1772
2	#5 Ctd. offset	1.24	8	1.04	1.8	63.5	41.7	29.56	0.1688
3	#3 Ctd. offset	1.31	5	1.17	1.65	59.1	36.6	37.86	0.1737
4	#5 Ctd. offset	1.25	7	1.11	1.8	57.9	34.6	31.11	0.1713
5	#5 Ctd. offset	1.27	6	1.43	2.11	53.7	32.5	37.02	0.161
6	#1 Ctd. offset	1.34	1	0.59	1.01	76.1	53.3	23.48	0.1747
7	#1 Unctd. offset	0.86	12	2.71	5.57	9.6	4.7	1.704	0.2661
8	Uncalendered nwspr.	0.76	15	5.15	7.3	4.2	2.7	0.7554	0.2795
9	Calendered nwspr.	0.82	14	2.05	3.20	10.6	5.4	2.577	0.2765
10	#3 Ctd. offset	1.33	2	0.85	1.35	70.6	48.5	110.1	0.1746
11	#1 Unctd. offset	0.90	10	3.26	7.18	4.0	2.5	0.7362	0.2795
12	#1 Ctd. offset	1.33	3	0.24	0.72	82.7	59.1	1024	0.1803
13	Tyvek	0.87	11	3.20	4.26	8.9	5.0	2.747	0.3521
14	#3 Ctd. gravure	1.22	9	0.97	1.15	56.7	35.6	61.76	0.1815
15	#3 Unctd. offset	0.83	13	2.72	6.03	5.0	2.9	1.524	0.2727

Appendix A-II Optical properties

Run No.	Test print data			Optical property data					
	Paper grade/type	Density range		R_o	R_∞	Printing opacity	Scattering power	Absorbing power	Fluorescence
		Value	Rank						
1	#1 Ctd. offset	1.32	4	86.9	89.6	97.0	9.09	0.05	2.11
2	#5 Ctd. offset	1.24	8	75.0	79.5	94.3	4.23	0.11	1.22
3	#3 Ctd. offset	1.31	5	69.1	73.4	94.2	3.39	0.16	0.09
4	#5 Ctd. offset	1.25	7	72.0	74.6	96.5	4.35	0.19	0.09
5	#5 Ctd. offset	1.27	6	75.1	78.3	95.9	4.69	0.14	0.07
6	#1 Ctd. offset	1.34	1	86.4	89.0	97.1	8.85	0.06	2.29
7	#1 Unctd. offset	0.86	12	77.6	83.6	92.8	4.41	0.07	1.35
8	Uncalendered nwspr.	0.76	15	61.0	64.8	94.1	2.60	0.25	0.10
9	Calendered nwspr.	0.82	14	60.1	63.5	94.6	2.60	0.27	0.10
10	#3 Ctd. offset	1.33	2	81.2	85.4	95.0	5.75	0.07	3.68
11	#1 Unctd. offset	0.90	10	90.0	93.4	96.3	10.76	0.02	6.73
12	#1 Ctd. offset	1.33	3	86.9	88.2	98.6	11.12	0.09	2.57
13	Tyvek	0.87	11	91.8	96.7	95.0	11.87	0.01	0.01
14	#3 Ctd. gravure	1.22	9	74.5	77.6	95.9	4.56	0.15	0.11
15	#3 Unctd. offset	0.83	13	79.9	84.2	95.0	5.41	0.08	0.07

Appendix A-III Permeable properties

Run No.	Test print data			Permeable property data		
	Paper grade/type	Density range		Parker porosity	K/N density	Croda red density
		Value	Rank			
1	#1 Ctd. offset	1.32	4	1.14	0.05	0.17
2	#5 Ctd. offset	1.24	8	1.16	0.07	0.14
3	#3 Ctd. offset	1.31	5	1.16	0.06	0.13
4	#5 Ctd. offset	1.25	7	1.18	0.07	0.13
5	#5 Ctd. offset	1.27	6	1.18	0.07	0.15
6	#1 Ctd. offset	1.34	1	1.15	0.05	0.17
7	#1 Unctd. offset	0.86	12	1.65	0.28	0.59
8	Uncalendered nwspr.	0.76	15	2.70*	0.34	0.89
9	Calendered nwspr.	0.82	14	1.58	0.31	0.70
10	#3 Ctd. offset	1.33	2	1.18	0.06	0.19
11	#1 Unctd. offset	0.9	10	2.95*	0.41	0.96
12	#1 Ctd. offset	1.33	3	1.50	0.10	0.23
13	Tyvek	0.87	11	2.15	0.24	0.85
14	#3 Ctd. gravure	1.22	9	1.22	0.09	0.23
15	#3 Unctd. offset	0.83	13	2.00	0.36	0.91

* Read on B scale