Predicting Sheet Structure Effect on Ink Oil Contribution to Print Through of Newsprint

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Keywords: Newsprint, show through, porosity, thickness

Abstract

With the current trend towards lower basis weights for newsprint, pressroom performance issues such as print through are becoming more serious. In this report, we introduce a systematic method of quantifying the effect of non-drying coldset ink vehicle oil on the opacity of paper. This new approach allows us to predict (with high accuracy) paper's contribution to the negative effect of ink oil on print through. We demonstrate that the contribution of the oil to print through is inversely proportional to the pore volume of the sheet, which is defined as the product of the paper's porosity and caliper. Since ink oil contributes up to 70% to the measured print through, it is essential to control both porosity and caliper. Evaluation of 12 different newsprints with basis weights of 45 and 48 g/m^2 showed that the use of deinked pulp as well as the filler can reduce the porosity of paper, thus leading to an increased propensity to opacity loss. Calendering the paper to a lower caliper helps smoothness, but reduces the pore volume, thus aggravating the print through problem.

Introduction

The average basis weight of Canadian newsprint is decreasing, and the use of deinked pulp (DIP) is increasing, for both economic and environmental reasons. Canadian mills are facing quality challenges from European producers, who

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operate more modern machines and possess more experience in producing newsprint grades with a basis weight as low as 40 g/m^2. One common performance problem is print through, which has become more severe as basis weight is reduced.

Print through is the undesired appearance of an image on the reverse side of the print. Nearly all newspapers and a significant amount of low-end commercial and directory publications are printed with non-drying oil-based coldset inks. With such inks, the magnitude of print through is controlled by three factors (Bristow 1987, De Grâce 1993): the initial opacity of the unprinted paper, penetration of ink pigments into the sheet, and loss in opacity due to ink vehicle oil that fills paper pores and reduces the effective scattering area of air-fibre interfaces. The non-drying ink oil may cause up to 70% of the measured print through (Erkisen 2007). At the same time, newsprint pore structure is known to be the main paper factor affecting its propensity to lose opacity. In this work, we have developed a systematic approach to studying the effect of ink oil on print through of paper. The effect of newsprint parameters such as the amount of deinked pulp (DIP) or fillers, basis weight, and calendering can now be consistently explained.

We tested 12 different newsprints from six Canadian mills and one Asian mill. The list of the samples including basic paper properties is reported in Table 1. The letter in the sample ID denotes the mill, and the number identifies different papers produced on the same or different paper machines. Sample “F1-Cal” is the paper “F1” that was further calendered in the lab from its original PPS roughness of 5 µm to 3.5 µm in order to approximately match the average roughness of the other samples. Solid black prints were made on a Prüfbau laboratory press at multiple print density levels (PD) ranging from 0.4 to 1.1. The prints were made with a North American coldset oil based ink (Ink 1). Some papers were also tested with an Asian coldset ink (Ink 2). In the printing test, we measured the ink requirement (IR), the amount of ink in g/m^2 required to attain a given target print density on the paper. The print density was corrected to account for the reflectance of unprinted paper:

$$PD = \log\left(R_\infty / R_p\right) \quad (1)$$

where R_∞ is the reflectance of the unprinted sheet and R_p is the reflectance of the solid print. Each sample was tested on both sides. The results of optical tests are shown in Table 2.

ID	Basis weight, g/m^2	Furnish	Ash, %	Caliper, µm	Bendtsen hardness		PPS roughness S10, µm	
					Side 1	Side 2	Side 1	Side 2
A1	45	100%TMP	0	78	2.30	2.30	3.53	3.20
A2	48	100%TMP	0	85	2.27	2.38	3.85	3.39
B1	48	100%TMP	0	85	2.50	2.24	3.89	3.81
B2	45	100%TMP	0	80	2.28	2.22	4.13	4.11
C1	48	94%TMP +6% Filler	6	76	2.73	2.55	2.93	3.08
C2	48	26% TMP +74%DIP	3.2	77	2.38	2.36	3.19	3.28
D	45	50% TMP +50%DIP	3.6	78	2.34	2.37	3.89	4.05
E	45	50% TMP +50%DIP	3.5	74	2.37	2.39	4.55	4.00
F1	45	100%DIP	7.5	72	1.86	1.81	4.55	5.00
F1-Cal	45	100%DIP	7.5	55	2.28	2.29	3.58	3.54
F2	45	100%DIP	8.4	72	1.79	1.96	5.26	4.55
G	48	100%DIP	10.0	65	1.65	1.75	4.95	4.37

Table 1. Newsprint composition and properties.

ID	Opacity, %		Ink1 requirement at PD=0.85, g/m^2		Ink1 requirement at PD=1.0, g/m^2		Ink2 requirement at PD=1.0, g/m^2	
	Side 1	Side 2	Side 1	Side 2	Side 1	Side 2	Side 1	Side 2
A1	94.67	94.39	1.56	1.50	2.63	2.59	2.33	2.16
A2	95.23	95.12	1.58	1.53	2.65	2.65	NA	NA
B1	94.68	94.86	1.59	1.63	2.70	2.78	NA	NA
B2	92.21	92.29	1.57	1.62	2.60	2.72	2.24	2.15
C1	96.50	96.56	1.29	1.27	2.17	2.13	NA	NA
C2	95.60	95.65	1.54	1.54	2.64	2.53	NA	NA
D	95.96	95.58	1.59	1.59	2.90	2.96	2.38	2.40
E	94.58	95.62	1.64	1.56	2.76	2.74	2.41	2.38

F1	95.32	95.63	1.93	2.11	3.53	3.96	NA	NA
F1-Cal	97.22	98.35	1.69	1.61	2.94	3.13	NA	NA
F2	96.52	96.61	2.04	1.92	4.24	3.81	3.39	3.06
G	97.05	97.18	2.59	2.38	>6	>6	5.64	4.89

Table 2. Printing test results.

We report the ink requirement at two levels of PD (PD = 0.85 and PD = 1.0). The fraction of ink transferred from the printing roll to the paper surface reaches its maximum at $PD \approx 0.85$. PD=1.0 is within the range of target print densities for most newspaper and commercial pressrooms. In the print through tests, we measured the total Print Through (PT) and the print through after ink vehicle oil extraction with petroleum ether (PTE). The difference between them is the Print Through of Oil (PTO), a measure of the opacity loss caused by the ink oil.

$$PTO = PT - PTE \tag{2}$$

The results of the print through tests are discussed in the next section. In addition, we measured the pore size distribution of the samples using mercury intrusion porosimetry. The results are discussed in the last section.

Effect of Paper Surface Structure on Print Through

Our study of print through confirmed previous observations (De Grâce 1993) that PTO linearly increases with the amount of ink on paper, Y (*Figure 0*). The lowest observed R^2 of the linear regression of PTO as a function of Y was 0.98. The slope of the line PTO vs. Y can be taken as a characteristic of the paper's propensity to lose opacity. The slope represents the increase in the print through due to the oil and is measured in inverse units of Y. We call this the Oil Gain Factor (OGF). A higher OGF indicates faster loss in opacity with increasing

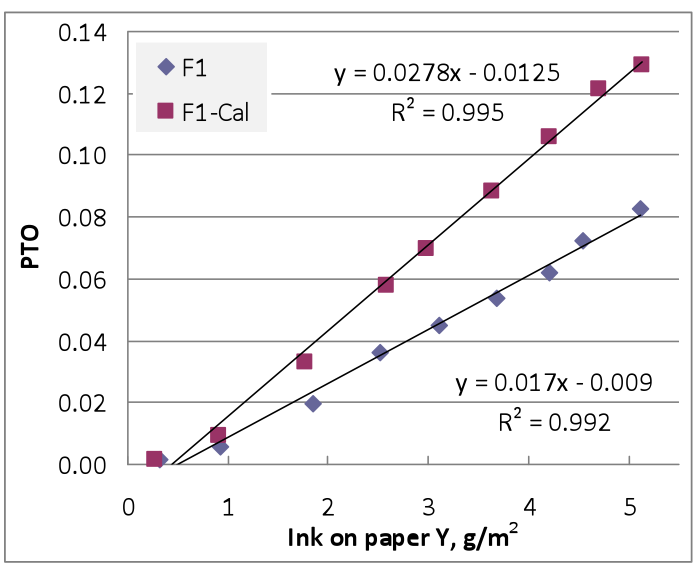

Figure 0. Print through due to oil as a function of amount of ink on the paper

amount of ink on paper. The example in *Figure 0* illustrates that an increase in the magnitude of PTO – the print through due to oil – is well predicted by the increase in the OGF. At the same level of ink on paper, different papers may exhibit different levels of print through. Using the definition provided above, we calculated OGF for each side of all 12 newsprints studied in this work (see *Figure 0*).

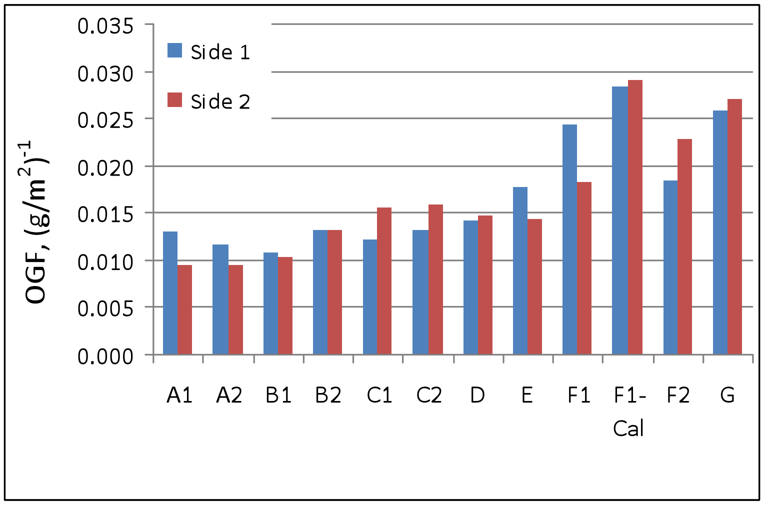

Figure 0. Oil Gain Factor of 12 newsprints printed with Ink1.

Figure 0 Ink 1 requirement at PD=0.85

First, we note that the extent of print through depends on the side of the paper. In *Figure 0*, we compared the OGF parameter on opposite sides of each sample.

To our knowledge, the two-sidedness in the oil penetration rate into the paper that we observe in *Figure 0* has not been discussed in the literature. In many samples, the difference in OGF between two sides can be very significant. It cannot be explained by possible deviations in the linear regression used to calculate OGF, because the accuracy of the linear fit was always extremely high (R^2>0.98).

In order to find an explanation for the OGF two-sidedness, we first need to better understand the paper structure and its interaction with ink oil. The OGF describes the propensity of the paper's pore structure to permit the penetration of ink oil into the sheet. It characterizes the inability of paper to hold the oil on the surface and prevent it from filling up deeper pores, therefore destroying more air-fiber interfaces. It is important to understand the difference between the ink requirement of paper – the amount of ink required to attain a given print density - and the efficiency with which the oil penetrates through the sheet, enhancing print through. Although some papers may require more ink to attain a commercial level of PD, it does not necessarily imply that the paper would also have more print through problems. The best example for such behavior can be found if we compare IR (see Figure 0) and the OGF two-sidedness. For instance, sample F1 requires more ink on Side 2 (Figure 0) but its OGF is larger on Side 1 (*Figure 0*). Another example can be found with samples C1 and C2. Their IR is almost independent of the paper side but the oil gain factor is very two-sided.

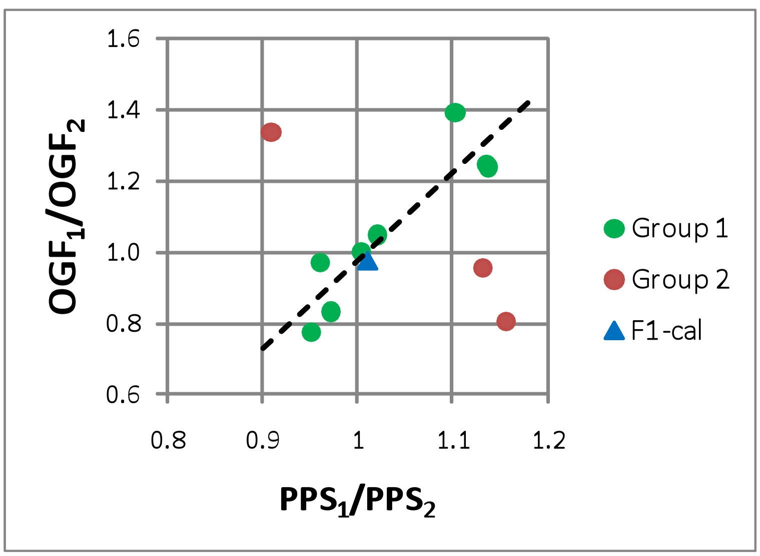

Figure 0. Two-sidedness of samples.

In order to explain the OGF two-sidedness, we compare it to the relative difference of PPS roughness between two sides (see *Figure 0*). We observed that for 8 out of 12 samples (A to E – Group 1) OGF ratio correlates fairly well with PPS roughness ratio. For 3 other samples that were made of 100% DIP (F to G – Group 2), the relationship seems to be completely reversed. We also note that calendering of the sample F1 almost eliminated the PPS roughness two-sidedness as well as the difference in OGF between the two sides.

Before trying to understand if the Group 2 samples show some anomaly or not, we would like to discuss the results for Group 1 samples. The fact that the fitted line has a positive slope indicates that the rougher side has a larger OGF value and therefore exhibits greater loss in opacity and more print through due to ink oil. Since the fitted line passes through the point (1,1), we can argue that the two-sidedness in OGF can be eliminated if surface roughness two-sidedness is eliminated. That is also confirmed with sample F1-cal whose initial OGF two-sidedness has been eliminated together with PPS two-sidedness by calendering.

Since the PPS roughness test is based on the air-leak mechanism, the result should represent both the surface topography of paper and the permeability of surface pores. Here, a difficult question is to estimate their relative contribution to the PPS test result. Conventional wisdom tells us that a topographically rougher surface should require more ink to attain a given level of print density. On the other hand, IR should be less sensitive to the permeability of the surface pores. IR measurement at PD=0.85 (Figure 0) shows that the papers of Group 1 have approximately the same level of IR although their PPS roughness varies across a wide range. An explanation of this phenomenon can be found in the effect of surface hardness on PPS roughness measurement and on the printing results. The Bendtsen hardness test clearly showed (Table 1) that the surface of Group 1 samples is highly conformable (larger number in the test) and very similar for all samples of that group.

In order to simplify the discussion of surface hardness, we introduce a measure of Compressibility of Surface Roughness (CSR) based on the Bendtsen hardness values:

$$CSR = \left(1 - \frac{1}{Bendtsen}\right) \cdot 100\% \qquad (3)$$

The advantage of CSR is that its range and physical meaning is easier to understand than that of Bendtsen values. CSR is 0% for uncompressible surface and increases with surface compressibility towards 100%.

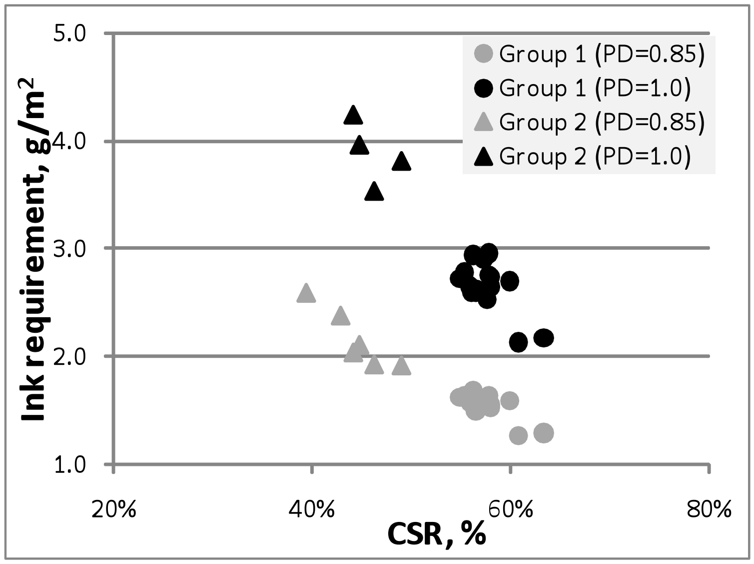

Figure 0. Ink 1 requirement vs. Compresibility of Surface Roughness (CSR).

Now, if we compare CSR with IR (*Figure 0*), the relationship between surface compressibility and ink requirement becomes evident. Moreover, the plot clearly demonstrates the grouping of the samples. Group 1 samples have a relatively small variation in IR that is well reflected by small spread in CSR values. We can argue that the high surface compressibility of Group 1 samples results in high conformability of the surface to the printing disk. In other words, regardless of initial topographical roughness of the papers in Group 1, their surface is well flattened in the printing nip resulting in approximately the same ink requirement level. In the PPS roughness test, we apply a clamping pressure to the measuring annulus. That has a similar effect on the paper surface. The macroscopic topographical roughness of samples in Group 1 should be reduced significantly under the clamping pressure and the PPS test should better reflect the surface pore structure. With that we conclude that a positive correlation between OGF ratio and PPS ratio of Group 1 samples in *Figure 0* is due to the surface pore structure as measured by PPS. We also note that although the surface topography should have a smaller effect on PPS results of Group 1 samples, it may be not negligible for some of the papers. That could explain the deviation of Group 1 points in *Figure 0* from the solid line.

In light of the discussion of Group 1 samples, we understand now that an explanation for the behaviour of Group 2 samples (see *Figure 0*) should be sought in the effect of surface compressiblity on PPS roughness test. In *Figure 0*, we observe that the samples of Group 2 have a smaller compressibility of surface roughness. Therefore, their surface roughness should be more resistant to applied load as confirmed by IR data in *Figure 0*. The same mechanism applies to the PPS roughness test. The contribution of paper surface topography to PPS roughness results in Group 2 should be more significant if not dominant compared to Group 1.

We are not aware of any test that would allow us to eliminate the effect of surface topography in measuring the pore structure of the surface layer of paper. In order to obtain additional information about the micro-structure of paper surface of the samples in Group 2, we used an optical surface profilometer. The dimensions of surface profiles were 10mm by 10mm and the resolution was 5 µm. We calculated power spectrum of the surface profiles and split it in several wavelength bands. The results are shown in *Figure 0*.

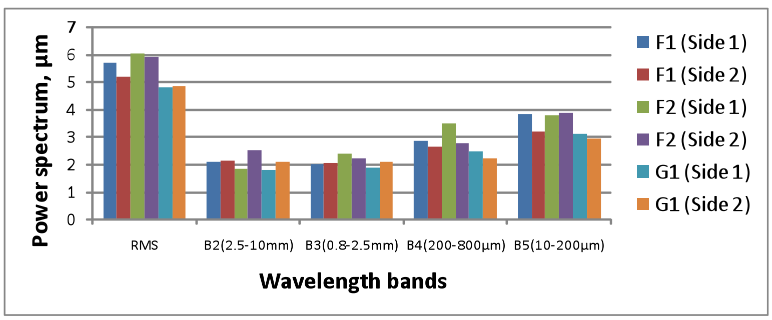

Figure 0. Power spectrum of surface profile (RMS—root mean square roughness).

The wavelength band B5 from 10 to 200 µm corresponds to the typical range of fibre width or dimensions of fines forming the surface pores. The scale is also more appropriate to the dimensions of the PPS annulus. The annulus width is 51µm while the radius is approximately 17.5mm. We can argue that if the paper surface is strongly conformable (Group 1), any large scale roughness would be flattened out under the loaded annulus. Therefore, we would be mainly measuring the roughness on a micro-scale comparable with the width of the annulus. It is the micro-scale that is of greater importance for the OGF parameter, because it determines how well the oil distributes on the surface and how deep it could propagate into the sheet even after printing.

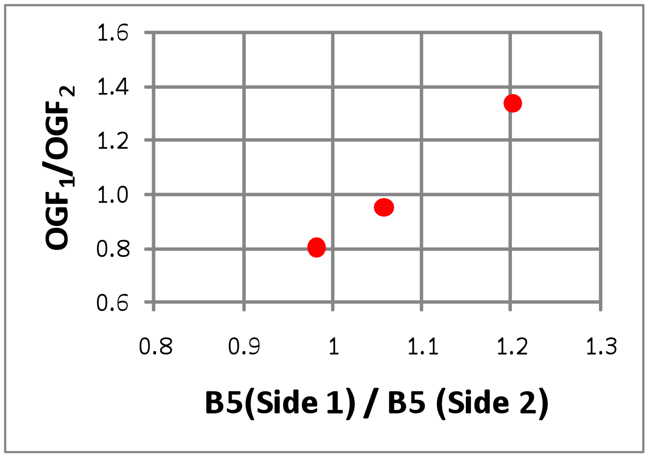

Figure 0. OGF two-sidedness vs. micro-roughness two-sidedness in band B5.

Now, we can compare relative difference of micro-roughness in the band B5 with that of OGF. The results of the comparison on three samples of Group 2 are presented in Figure 0. As we expected, the large OGF two-sidedness of samples F1 and F2 matches the micro-roughness two-sidedness observed in *Figure 0*. As opposed to the large PPS two-sidedness of paper G (Table 1), there is very little difference between two sides on the micro scale as determined by B5 spectrum. That could well be within the variation from sample to sample. This fact goes in line with the observed small difference in OGF values between two sides of paper G.

To conclude this section, we note that the calendering performed on sample F1 was very effective in eliminating the two-sidedness issue. It has also reduced the surface hardness and decreased IR level. However, the average level of print through as characterized by OGF has significantly increased. We will provide an explanation to this phenomenon in the last section, where we discuss the effect on OGF of the pore structure in the bulk of the sheet.

Effect of Ink on Print Through

In order to see if any properties of the ink itself can affect OGF, we printed some papers with an Asian ink (Ink 2). The ink requirement results for Ink 2 are presented in Table 2. Comparing IR for the two different inks in Figure 0, we first observe that the grouping of samples with high and low surface compressibility is preserved. We also note that the ink requirement difference between inks slowly increases with the amount of ink on paper. The Asian Ink 2 has a significantly higher viscosity than the North American Ink 1. Since the variation in IR of different samples is due to the level of their surface compressibility (CSR)—the ability of the surface to flatten out in the printing nip—we can conclude that for papers with lower compressibility of surface roughness the choice of ink is critical. The ink with higher viscosity will have lower mileage – less ink will be consumed to attain a required print density. For

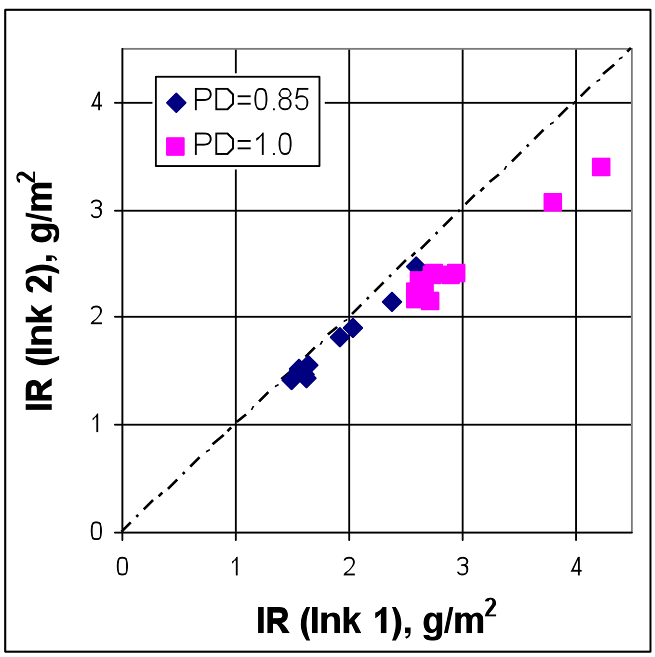

Figure 0. Comparison of ink requirement for two inks at PD=0.85.

papers of high CSR (such as those in Group 1), the ink viscosity is less important in terms of IR.

A comparison of OGF results for the two inks is presented in *Figure 0*. The data indicate that between two samples if one is more prone to lose opacity with Ink 1, it would also be more prone to the loss in opacity with Ink 2. This supports the argument that the OGF reflects some physical property of the paper, and allows different papers to be ranked according to their propensity to lose opacity, regardless of the coldset ink used. On the other hand, we can conclude that depending on the properties of the ink oil, the absolute magnitude of OGF can vary. For example, the fact that all points in *Figure 0* lie below the diagonal means that the Ink 2 gives qualitatively better print through performance for any of the papers. This means that the inks themselves can be compared by their propensity to increasing print through. That Ink 2 is more viscous results in less print through problems.

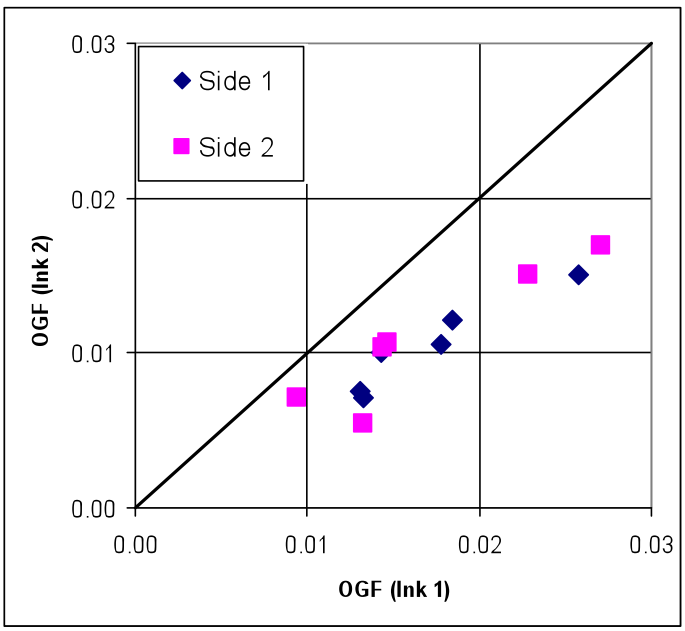

Figure 0. Comparison of OGF measured with two inks.

In the previous section we concluded that the two-sidedness in oil gain factor is due to the surface pore structure of paper. The fact that higher oil viscosity helps reducing OGF supports the assumption that the magnitude of oil spread and penetration into the sheet is strongly related to the pore structure of paper. In the following section, we directly measure the pore structure of the samples and relate it to the OGF parameter.

Effect of Paper Pore Structure on Print Through

From the above analysis, we have demonstrated that the OGF provides a good quantitative prediction of the paper's propensity to lose opacity due to ink oil. Although its absolute value may depend on the oil properties, the OGF reflects some intrinsic characteristics of paper and allows different papers to be compared with respect to their propensity to print through. The early works on the ink oil contribution to print through (Bristow 1987, De Grâce 1993, Pauler 1982) clearly showed that the pore structure of the sheet is certainly the key factor. However, it is unclear how the porous structure of paper actually affects the print through: Is pore volume, or pore size or a combination with other paper property important? The analysis of pore size distribution of the samples allowed us to quantitatively confirm the direct relationship between OGF and pore structure.

The mercury intrusion test provides the information about the pores in the size range from 0.1 to 100 μm. By using the Washburn equation, the intrusion data can be represented as a graph of pore volume against the pore diameter. An example of the graph is shown in *Figure 0* where the y-axis corresponds to log-differential intrusion volume. The log-differential plot is a convenient representation of the pore size distribution in terms of volume occupied by pores of given diameter when the diameter is plotted on a log scale (for details see Meyer 1999). It was shown in the literature that the pore size distribution of paper can be approximated by a log-normal distribution (Corte 1966, Dodson 1996). According to that function, the log differential volume of large pores should decrease exponentially to zero on the log scale of pore diameter. Indeed, assuming that the volume V of a single pore is proportional to the cube of pore diameter D, we obtain for the log differential volume:

$$\frac{\Delta V}{\Delta \log D} \sim D^3 \, e^{-\frac{(\ln D - \mu)^2}{2\sigma^2}} = \exp\left[-\frac{(\ln D - \mu)^2}{2\sigma^2} + 3\ln D\right] \tag{4}$$

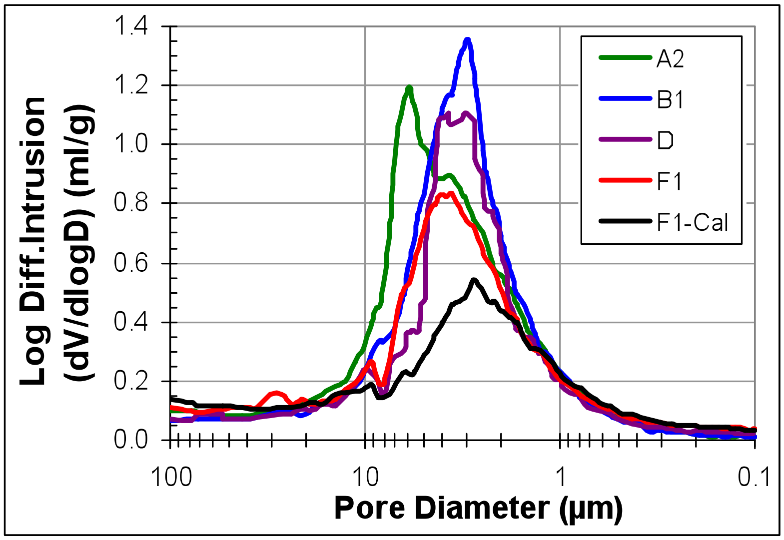

Figure 0. Pore volume distribution.

However, the mercury intrusion measurements on real paper showed that for pore diameters larger than 20µm the log differential volume levels off or sometimes can even increase towards very large pores (see *Figure 0*). For newsprint sheets of thicknesses about 50–80 µm, pore diameters larger than 20µm should be associated with surface roughness rather than with true internal pores. Hence, in what follows the analysis of mercury intrusion data is limited to the range from 0.1 to 20 µm. In order to simplify the analysis of the pore size distribution, some physical characteristics of the distribution were calculated (Table 3).

Sample ID	Intrusion Volume, mL/g	Total Pore Area, m²/g	Porosity, %	AVG Pore D, µm	Average OGF, $(g/m^2)^{-1}$
A1	0.82	1.46	55.07	2.23	0.0112
A2	0.79	1.39	54.36	2.29	0.0106
B1	0.79	1.46	54.15	2.16	0.0106
B2	0.83	1.41	55.45	2.36	0.0132
C1	0.72	1.80	52.67	1.61	0.0139

C2	0.73	1.53	52.68	1.91	0.0145
D	0.73	1.53	52.53	1.90	0.0145
E	0.71	1.51	52.07	1.89	0.0161
F1	0.66	1.57	50.62	1.68	0.0213
F1-Cal	0.46	1.42	41.57	1.29	0.0287
F2	0.58	1.56	47.49	1.50	0.0207
G	0.44	1.31	40.66	1.34	0.0264

Table 3. Mercury intrusion results and average OGF values.

The average pore diameter in Table 3 is calculated based on a cylindrical approximation of pore shape:

$$D_{avg} = \frac{4V}{A}, \tag{5}$$

where V and A are the total intrusion volume and the total pore area, accordingly.

Since the mercury intrusion cannot provide information on the two-sidedness in the pore size distribution, we also reduced the OGF two-sidedness information to a single OGF value that is the average over the two values obtained for each side of the paper. Conventional wisdom tells us that the effect of ink oil on the opacity of paper should be related to the number and volume of pores available in the sheet. The sheet porosity is a standard measurable characteristic of the relative pore volume. When multiplied by the paper thickness it provides a quantitative measure of the total pore volume per square meter of paper—V_p. Comparing the pore volume with OGF (see Figure 11), we found a very strong

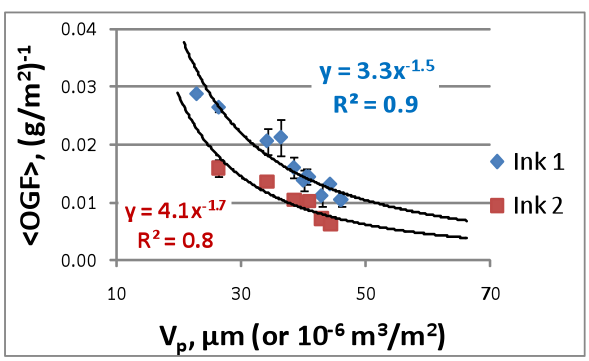

Figure 0. OGF as a function of pore volume V_p.

correlation. The graph shows that the rate at which the paper loses opacity with increasing amount of ink oil is inversely proportional to V_p.

This result is not surprising. If two papers have the same caliper but different porosities, the oil can travel deeper through the thickness of the sheet of lower porosity, because it has smaller pore volume to fill in the paper plane. On the other hand, when two papers have the same porosity but different caliper, the oil can reach the other side of the paper of smaller caliper faster and therefore provide the light with direct channel to propagate through the sheet without much scattering. Papers with lower porosity or caliper would be therefore more prone to the print through problems. The overall form of OGF as a hyperbolic function of V_p also agrees with expected asymptotical behavior of print through propensity. Indeed, when the pore volume increases to large values, the propensity to print through OGF should fall to zero. And vice versa, if the paper has little pore volume, the ink should quickly fill the paper pores resulting in fast increase of PTO. That should transfer to very large values of OGF.

In the article by De Grâce (1993), OGF was plotted against the amount of fines in 19 newsprints with 0% DIP content. The correlation with the amount of fines was found to be lower (0.74) than we observe here with pore volume. We explain the difference by the fact that the primary paper characteristics determining OGF is the porosity and caliper. The porosity, for example, can be affected by the total amount of fines, but there could be other independent factors. In particular, furnish composition such as DIP content may result in a better consolidation of the sheet and therefore lower porosity and higher OGF (see Table 3 and *Figure 0*).

Indeed, in our study, newsprints with higher DIP content had lower porosity and higher propensity to print through as characterized by OGF. Fillers also have a strong negative effect on print through propensity of paper, because they fill up large pores, shift the pore size distribution towards smaller pores and therefore reduce the sheet porosity (De Grâce 1993, Pauler 1982). This effect can be observed with sample C1 that has a filler content of 6%. Regarding the caliper, we note that two extreme points of low porosity in *Figure 0* correspond to the samples F1-Cal and G. Although they have a very similar porosity, the difference in OGF is well explained by the difference in their caliper.

Conclusions and Implications for Papermakers

The propensity of newsprint to lose opacity due to ink vehicle oil can be described quantitatively by the Oil Gain Factor (OGF). Although the absolute value of this parameter depends in part on the properties of the ink, the relative differences in OGF represent some fundamental differences in paper structures. We also demonstrated that OGF can be different for different sides of the paper due to difference in surface pore structure as characterized by PPS roughness measurement. We showed that for papers with small compressibility of surface roughness (CSR), PPS roughness test may not be adequate for characterizing the two-sidedness in surface pores. We demonstrated that the magnitude of OGF averaged over two sides of paper correlates very well with the pore volume.

Comparing samples containing different amounts of DIP, we observed that increasing the DIP content in the furnish decreases the sheet porosity and therefore increases the paper propensity to the loss in opacity. Normally, the deinked pulp increases the opacity of the paper. However, its cumulative effect on the total print through propensity of the paper should be assessed by taking into account the negative effect of DIP on the Oil Gain Factor. The same effect was observed by adding filler to the paper, because the filler reduced the sheet porosity. Hence, we recommend analyzing the benefits of adding some DIP or filler to the furnish by evaluating their concurrent effects on the sheet opacity and on the loss of opacity due to ink vehicle oil. Since the ink oil properties affect the absolute values of OGF, we recommend using the same reference ink for comparing different papers.

Finally, we note the existence of a constant theme in the published literature from the mid-1970s onwards, stating that printers wishing to move to lower basis weight for coldset printing must involve their ink supplier. The negative effect of decreasing caliper of low basis weight newsprint can be compensated by choosing an ink of higher strength—that is, containing more pigment and less oil. Such an ink would also have a higher viscosity, as with Ink 2 in this study.

Acknowledgments

The authors would like to thank Jöelle Grenon for performing many of the tests used in this work. We would also want to thank Joe Aspler for insightful discussions and for improving the text of the paper.

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