PULP AND PAPER PROPERTIES AFFECTING THE LINTING PROPENSITY OF PAPER: FUNDAMENTALS.

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Abstract:
Little is known on the pulp and paper properties controlling the fibre removal in a printing nip, the source of linting in offset printing. The linting propensity of pulps and papers was studied by printing on British handsheets made of different combination of thermomechanical pulp, stone groundwood, low yield sulphite. The linting propensity tests used were the IGT pick test, the Varkaus method, modified and not, and the number, cumulated length, and distribution of fibres removed while printing at different speeds on a laboratory printing press. Fundamental relationships between some pulp properties such as specific surface of fibres and bond strength, and paper structural parameters such as porosity are proposed and the linting propensity of pulps and paper are proposed. It is found that the relationships are not only non-linear in nature but include both pulp and paper properties.

INTRODUCTION

In offset newspaper printing, linting is the tendency of paper to shed loosely bonded surface fibres and fines during printing. Linting not only causes deterioration in image quality **[Mangin, 1987]**, but the build-up of lint on the offset blanket, and within the offset press inking and dampening systems **[Mangin et al, 1990]**, creates problems in press operation. It is considered to be one of the most serious paper-related problems in offset printing **[Karttunen, 1975, Mangin, 1987, Wood/Karnis, 1990, Wood et al, 1993, Lindem/Moller, 1993]**.
Measuring lint accumulations on the blankets of a pilot offset press has been considered the ultimate test for linting **[Hugues, 1966]**. However, the linting propensity of paper is **not** the accumulation of lint material on an offset press blanket. Lint build-up results from the interaction between the paper linting propensity and the press parameters **[Mangin et al, 1990]**. The inherent complexity of the offset process prevents lint results obtained on any offset press to be generalized in terms of pulp and paper properties **[Mangin 1987, 1989, 1991]**. In other words, an offset press is not suitable to understand which, and how, paper and pulp properties affect the linting propensity of paper. Our findings and conclusions were recently confirmed by

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task forces whose objective was to evaluate the papermaking variables affecting the linting propensity of paper **[Wood *et al* 1993, Lindem/Moller, 1992]**.

The linting propensity of paper is mainly a fibre removal phenomena **[Mangin, 1988, 1992]** related both to fundamental pulp and paper properties, and to printing conditions. From a papermaker's perspective, it is logical to assume that the bonding potential between fibres and fines somehow controls the linting phenomena. Due to the absence of a physical model describing fibre removal in the printing nip, relationships between pulp and paper properties and the linting propensity of paper have not yet been established. Although a fibre removal model based on ink flow in the printing nip has recently been proposed **[Mangin 1988, Mangin/Silvy 1990]**, the new model only represents the first steps towards a more comprehensive approach. Simple basic information on how the pulp and paper properties affect the linting propensity of paper is still lacking. The objective of this paper is to establish, through model experiments, some fundamental relationships between the pulp and paper properties and the linting propensity of paper.

APPROACH

The inter-fibre bonding potential is usually evaluated by standardized physical tests performed on standard papers made on a British handsheet machine (BHM). Due to the differences in the fibre lay-down and the water removal processes, the structure of BHM-made papers is quite different from the one of commercial papers. In BHM papers fibres are randomly oriented, and a large portion of the fines, up to 30%, is not retained. As linting is a surface phenomena related to fines, the BHM has been modified to retain the fines by re-circulating the drained water, rich in fines.

Standard paper tests evaluate the pulp properties, i.e. the bonding potential of fibres inside the sheet but not the bonding potential of surface fibres. Considering that the properties of the surface layers of fibres are related, although non linearly, to the properties of the internal layers, some indication of the paper surface properties can nevertheless be deduced from those standard tests. Contrary to paper tests, printing interacts mainly with the surface layers. Notwithstanding the fundamental differences between commercial and BHM papers, printing tests can be performed on BHM papers to analyze the linting potential of the pulps, and, in a more limited fashion, of the papers. True commercial papermaking conditions would further modify the linting propensity of the paper made from a single mixture of pulps or furnish composition **[Mangin/Dalphond 1992, 1993]**. Accordingly, the resistance to surface fibres and fines de-bonding of pulps/papers as evaluated by fibre removal, has been measured by printing BHM samples on GFL and IGT laboratory presses.

EXPERIMENTAL

Samples Six sets of sheets were manufactured on a British handsheet machine (BHM) with various content of thermomechanical pulp (TMP), low yield sulphite (LYS), and stone groundwood (SGWD) pulps. The pulps originated from an eastern Canadian mill using mainly softwood. The furnish content used for the 6 samples are listed in **Table 1**. The furnish compositions pulp were chosen to include a large range of commercial newsprints.

Table 1. Furnish Content of Bristish Handsheets

Sample	TMP	LYS	SGWD
100 TMP	100	0	0
80 TMP	80	10	10
60 TMP	60	20	20
40 TMP	40	30	30
100 LYS	0	100	0
100 SGWD	0	0	100

Printing Two laboratory printing methods were used. The Varkaus method **[Kuvajaa, 1972]**, at constant-speed printing, and the IGT pick test, in accelerated-mode printing. Both methods have been improved to remove their major drawbacks when attempting to evaluate linting **[Mangin, 1988]**. The test printing conditions are presented in **[Mangin, 1988]**.

The pick resistance of a first series of paper samples has been evaluated according to the original Varkaus method **[Kuvajaa, 1972]**. In the method, overprinting three times, from an initial inking of 5 $g.m^{-2}$, ensures that the evaluation of the mass balance is accurate. The mass balance is based on the fact that during printing, while ink is transferred to the paper, fibres are transferred back to the printing plate. Both ink weight on the printing plate and ink transfer are evaluated from weighing the printing plates before and after inking, and after printing.

In order to identify the fibrous material removed during printing, IPI tack-graded ink No.3, used in the original Varkaus method, has been replaced by a model ink without carbon black pigment. The model ink is an ink vehicle composed of a 12 % resins solution in a pure mineral oil. The characteristics of the ink components have been described elsewhere **[Mangin/Dalphond, 1992, 1993, Mangin 1988]**. The ink tack (8) is slightly higher than for commercial offset newsinks (2.5 to 5.5). Although the tack of the IGT pick fluids was too high to be measured on the Inkometer, the IGT test method was not modified. It is the most common method to evaluate the resistance of papers to picking.

RESULTS AND DISCUSSION

Correlation Between Fibre Bonding and Standard Paper Tests

The pulp and fibres properties, and the structural, and mechanical properties of the BHM-made papers are presented in [**Mangin, 1988**]. **Figure 1** shows that, if the SGWD pulp is excluded, the internal bond Scott is linearly related to the burst index. In the burst test, the inter-fibre bonding of the whole fibre network is measured in the Z-direction, normally to the paper surface. Debonding is mainly related to a normal force. In the Scott bond test, paper is delaminated in an XY-plane parallel to the paper surface. Delamination usually occurs in the middle fibre layers as debonding is mainly caused through peeling. The differences between the debonding mechanisms explain that the SGWD sample is outside the expected linear correlation. From a physics standpoint, the x-axis in **Figure 1** represents a Z-bonding potential while the y-axis represents the XY-bonding potential. As expected, **Figure 1** also shows that the bonding potential of the chemical pulp (LYS) can be used as a reference point for a pulp with high bonding potential. In others words, papers made of 100% LYS pulp would present a minimum in linting propensity. Evaluating the various furnish compositions of TMP, SGWD, and LYS pulp is more complex. The bonding potential of the SGWD pulp is far superior to any furnish composition containing TMP, even with high contents (40%) of LYS pulp.

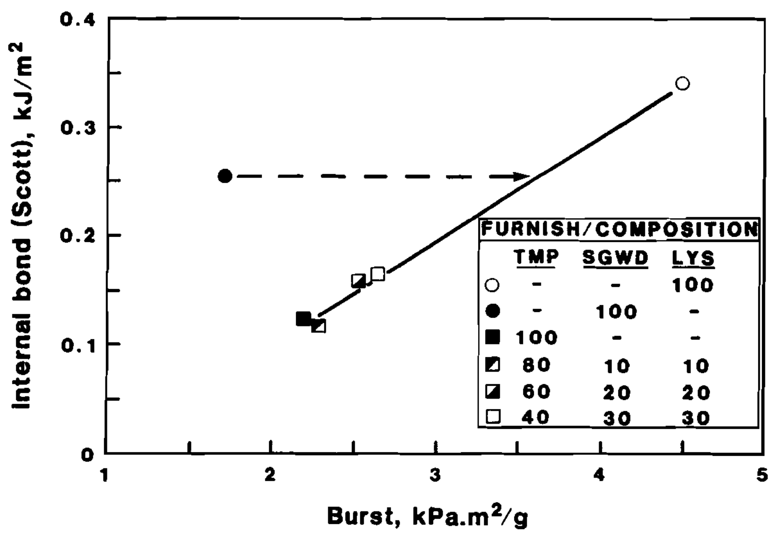

Figure 1 Internal Scott bond as a function of burst for BHM papers. SGWD pulp has a higher bonding potential than all furnish compositions containing TMP.

The high bonding potential of SGWD is further supported in **Table 2** which shows correlation levels between internal Scott bond and various indices related to the fibre bonding potential. When SGWD is excluded from the regression analysis, all standard physical tests but tear correlate with the internal Scott bond. For this purpose, only burst, tear, and breaking length have been shown. The correlations hold true for stretch (%), Tensile Energy Absorption (TEA, $mJ.g^{-1}$), and Tensile index ($N.m.g^{-1}$). In all these tests, the paper deforms under stress, with a probable shear between fibres layers, up to the breaking point. All regression coefficients (r^2) decrease significantly when the SGWD pup is included in the analysis.

Tear is measured perpendicularly to the plane of the paper surface. As expected, there is no correlation between tear, measured perpendicularly to the plane of the paper surface, and the internal bonding index, measured parallel to the plane of the paper surface.

Table 2 **Correlations Between Internal Scott Bond and Pulp Properties.**

Test/Property	Pulp	r^2	Intercept	Slope	SE
Burst Index, $kPa.m^2.g^{-1}$	- SGWD	0.997	- 0.089	+ 0.095	0.005
	+ SGWD	0.440	+ 0.035	+ 0.059	0.065
Tear Index (4-ply), $mN.m^2.g^{-1}$	- SGWD	0.223	+ 1.762	- 0.198	0.080
	+ SGWD	0.165	+ 0.373	- 0.024	0.079
Breaking Length, km	- SGWD	0.992	- 0.154	+ 0.067	0.008
	+ SGWD	0.473	- 0.018	+ 0.045	0.070
Zero Span Breaking Length (Pulmac), km	- SGWD	0.947	- 0.624	+ 0.069	0.021
	+ SGWD	0.206	- 0.097	+ 0.026	0.072

- SGWD excluded, + SGWD included in regression analysis
r^2 determination coefficient, SE standard error on estimated values.

The good level of correlation (r^2 = 0.947) found between the Zero Span breaking length suggests that, in addition to debonding, some fibres might have been torn during the internal bond test. However, due to the number of small fibrous debris contained in SGWD, this hypothesis could not be confirmed by microscopy.

The high bonding potential of the SGWD pulp is related to a higher number of fines, and higher degree of fibrillation in both fines and fibres, when compared to the TMP **[Mangin, 1988]**: both factors improving the fibre mat consolidation. The relationship between fines and fibres becomes apparent when the specific surface of the pulps are considered. For a given pulp, the specific surface provides an indication of the degree of fibre fibrillation. In this work, the specific surface was measured without removing the fines from the pulps. **Figure 2** shows that, for all pulps except SGWD, the internal Scott bond varies linearly as a function of the specific surface of fibres of the pulps and pulp mixtures. Again, the 100 SGWD pulp has a bonding potential higher than furnish compositions containing TMP, and even LYS up to 40%. It can be calculated that the bonding potential of SGWD is equivalent to the bonding potential of a pulp mixture of mechanical pulps (SGWD and TMP) and LYS of a 3.75 $m^2.g^{-1}$ specific surface. As the specific surface is linearly related to the percent of mechanical pulp **[Mangin, 1988]**, we calculate that the equivalent furnish composition would be 35% mechanical pulps and 65% chemical pulp (LYS).

In summary, the bonding potential of pulps, as measured on BHM randomly oriented papers, decreases as a function of the thermomechanical pulp content. The stone groundwood pulp has a far greater bonding potential than expected, equivalent to pulp furnish containing up to 60% of well-bonding chemical pulp. The 100% LYS pulp is used as a reference for high bonding potential.

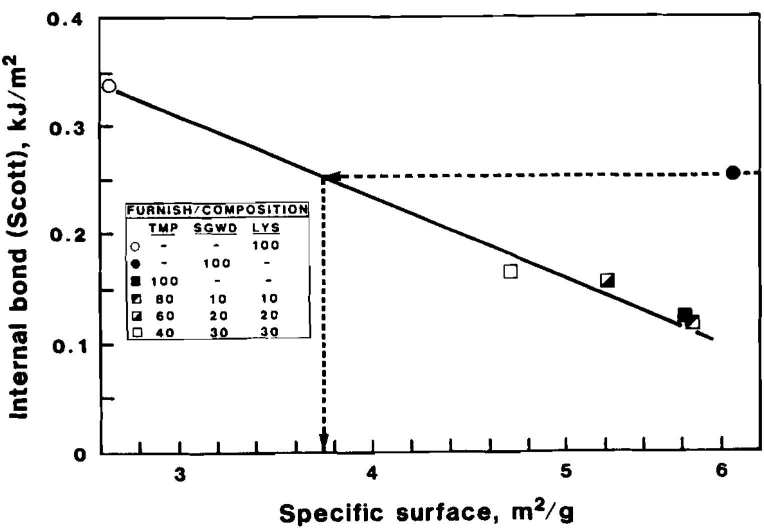

Figure 2 The internal Scott bond decreases as a function of the specific surface of the pulp fibres. SGWD pulp has a bonding potential far greater than expected from the regression analysis.

The Surface Bonding Potential of BHS Randomly Oriented Papers as Measured in Accelerated-Mode Printing (IGT Pick)

The resistance to surface fibre debonding measured in the accelerated-mode is done through the IGT pick test. For printing, the sector holding the sample is accelerated from the rest position (0 velocity) to a chosen pre-set speed (end-velocity). Evaluation of picking is to observe, under low angle illumination, the first or the 10th fibre **[Mangin, 1987]** picked from the paper surface. To remove subjectivity from the method, the picked fibres have been recuperated by washing the printing disc. The fibrous material was then weighed, and the fibre distribution analyzed with the Kajaani FS-100 fibre classifier.

Table 3 shows the picking speed or printing speed of the first picked fibre, the surface bonding energy as calculated from the velocity-viscosity product (VVP) **[Mangin et al, 1990]**, and the weight of fibrous material removed from the paper surface.

Table 3. IGT Pick Test or Accelerated-mode Printing Performed on British Handsheet Randomly-Oriented Papers.

Sample	End-Velocity, $m.s^{-1}$	Picking Speed[1], $m.^{-1}$	VVP[1], $J.m^{2}$	Fibre Weight[2], mg
100 TMP	4	***[3]	***[3]	2.38
	2	0.91	14.1	2.30
100 SGWD	4	***[3]	***[3]	0.59
	3	1.66	25.7	0.94
100 LYS	4	***[3]	***[3]	0.00
	4	0.78	42.0	0.26[4]
80 TMP	4	1.64	25.4	1.87
60 TMP	4	1.96	30.4	0.77
40 TMP	4	2.25	34.9	0.89

[1] coefficient of variation is 10.4%; [2] total weight of fibres removed from 5 strips, i.e. 0.01575 m^2
[3] could not be measured; [4] medium viscosity poly-isobutadiene oil

Figure 3 shows that, excluding TMP, the surface bonding energy, indicated by the VVP, decreases linearly as a function of the fibre specific surface. Considering how fibres are removed in the IGT pick test **[Mangin et al, 1990]** and the high bonding potential of the SGWD pulp, we conclude that TMP is the weakening pulp of all various compositions containing mechanical pulps. This is further supported in **Table 4**. **Table 4** shows that the correlations between the surface bonding energy, VVP or picking speed, and some standard paper tests, are not significant. As predicted from the poor bonding potential of the TMP, the correlations become marginally significant when the TMP is excluded from the regression analysis. This is however not valid for the internal Scott bond and for the Zero Span Breaking length (not shown here). However, a minimum in debonding resistance exists for the 100% or pure SGWD pulp. Finally, considering the possible effects of the paper structure on the fibre removal of surface fibre **[Mangin/Silvy, 1990]**, the surface bonding energy seems to decrease linearly (r^2 = 0.950) as a function of the air permeability of the BHM papers; but only when SGWD pulp is removed from the regression analysis (r^2 = 0.446 when SGWD is included). The BHM papers made from 100% SGWD have a very impervious structure as the fines have been recirculated and closed the paper surface.

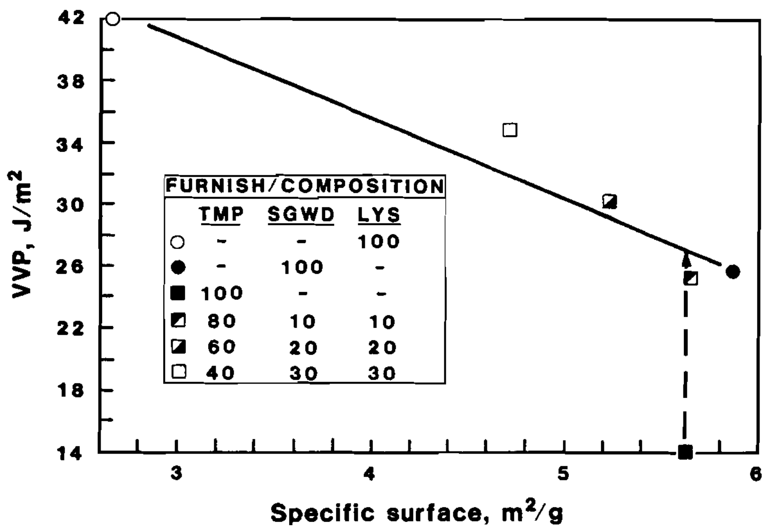

Figure 3 Linear relationship between pick resistance as indicated by the VVP and fibre specific surface. TMP is outside the linear correlation.

The number, dimension, and cumulated length of fibrous material removed from the paper surface are presented in **Table 5**. From **Table 5** data, we can further study the effect of fibre network structure and the presence of mechanical pulp fines (TMP and SGWD) on the fibre removal occuring in accelerated-mode printing.

Table 4. Correlations Between Surface Bonding Energy (VVP) and Paper-Pulp Properties.

Test/Property	Pulps	r^2	Intercept	Slope	SE
Burst Index, $kPa.m^2.g^{-1}$	*[1]	0.578	+ 9.03	+ 7.47	6.2
	**[2]	0.848[3]	- 71.3	+ 40.5	3.5
Tear Index (4-ply), $mN.m^2.g^{-1}$	*[1]	0.002	----	----	---
	**[2]	0.850[3]	+ 297	- 33.7	3.5
Internal Scott Bond, $kJ.m^{-2}$	*[1]	0.454	+ 14.5	+ 74.2	7.0
	**[2]	0.665	- 17.9	+ 315	5.2
Air Permeability P20, $mL.min^{-1}$	+ SGWD	0.446	+ 41.0	- 0.024	7.1
	- SGWD	0.950	- 54.6	- 0.044	2.3

*- TMP excluded, + TMP included in regression analysis; - SGWD excluded, + SGWD included in regression analysis; *[1] 6 pulps, **[2] 4 pulps, [3] standard error on estimated values are lower than the standard deviation on VVP (3.5 $J.m^{-2}$); $r^2 > 0.878$ is significant at the 95% confidence limits $r^2 > 0.805$ is significant at the 90% confidence limits*

Table 5. Number, Length, and Cumulated Length of Fibrous Material Removed in the IGT Pick Test.

Sample	Average Fibre Length, mm		Fibres	Cumulated Fibre Length, $km.m^{-2}$	
	L_1	L_2	Na $x10^{-4}$	La_1	La_2
100 TMP	0.68	1.58[1]	45.2	0.308	0.714
	0.76	1.40	29.9	0.228	0.419
100 SGWD	0.32	1.01[2]	25.7	0.082	0.260
	0.41	0.85	21.1	0.086	0.179
100 LYS	0.33	1.37	2.42	0.008	0.033
	0.31	0.72[3]	28.5[3]	0.088	0.204
80 TMP	0.65	1.28	27.4	0.178	0.350
60 TMP	0.55	1.10	17.4	0.096	0.191
40 TMP	0.50	0.97	19.7	0.098	0.190

L_1 arithmetic average fibre length, L_2 weighted average fibre length; Na number of fibrous elements removed per printed unit area; $La_1 = L_1.Na$ and $La_2 = L_2.Na$

Figure 4 shows the number of fibrous material: fibres and fines removed, as a function of the percent of TMP in the paper. As far as the number of fibrous elements is concerned, the minimum in fibre removal corresponds to the pure chemical pulp (100 LYS) while the maximum corresponds to the pure thermomechanical pulp (100 TMP).

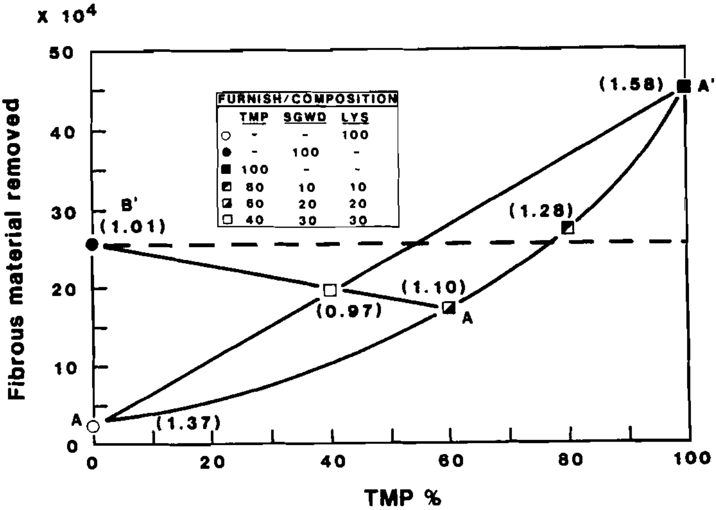

Figure 4 Number of fibrous elements removed per printed unit area as a function of the thermomechanical pulp content of the paper. The average fibre length is indicated into parenthesis. From such a graph, one can deduce the relative importance of long TMP fibres and SGWD fines on the fibre removal.

Microscopic analysis of the pulps revealed that the fibrous material removed from the various pulp mixtures (40, 60, and 80 TMP) contains less than 1 percent of chemical fibres (LYS). Both number and length of fibrous material removed increase according to the sequence: 100 LYS (0% TMP), 60, 80 et 100 TMP. The order reflects the actual proportion of TMP-LYS in the furnish composition.

Comparing the average length of fibrous material removed from the 100 SGWD: 1.01 mm, to the average length of fibrous material removed from 100 TMP: 1.58 mm, we further deduce that the number of long TMP fibres increases in the same sequence.

Similarly, fines in the stone groundwood pulp contribute to the surface bonding potential of the 40 and 60 TMP papers. For the 40 and 60 TMP samples, the number of fibrous elements removed is lower than the number of elements removed from the 100 SGWD (illustrated in

Figure 4 by a dashed line). In this domain, i.e. below the dashed line, mainly fines from the stone groundwood pulp are removed during printing. The low yield sulphite pulp then behaves as a strengthening pulp. Above the dashed line, i.e. for the 80 TMP sample, long TMP fibres, poorly fibrillated, are mainly responsible for fibre removal.

The combined effect of TMP fibres and SGWD fines on fibre removal is further illustrated in **Figure 5**. **Figure 5** shows the cumulated length of fibrous material removed per printed unit area as a function of the specific surface of the pulp fibres. The cumulated length increases as a function of the specific surface. **Figure 6** shows the number of fibrous elements removed during printing as a function of the air permeability of the BHM papers. The air permeability of the sheets is an indication of the porosity of the papers. It is related to the fibre network structure: i.e. the composition in fibres.

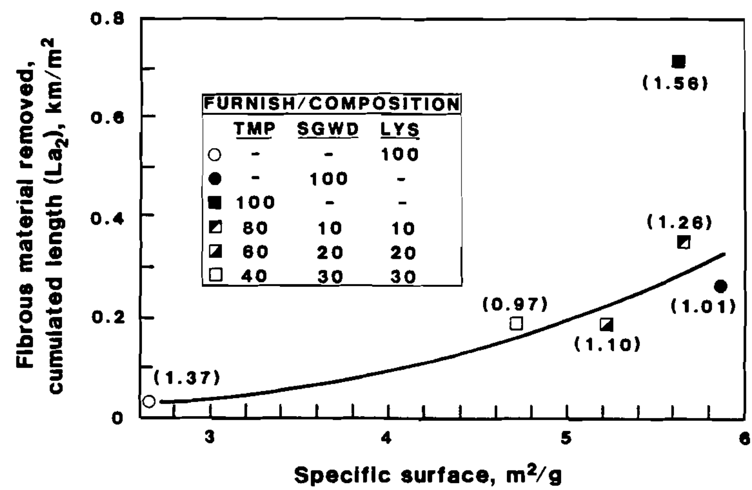

Figure 5 Cumulated fibre length removed per printed unit area as a function of the specific surface of the pulp fibres. TMP presents a maximum in fibre removal. The average fibre length is indicated into parenthesis.

Considering that the paper properties related to second order interactions between the various pulp fibres, are negligible when compared to the properties of the pulps (100%), the location of fibre removal points of any furnish composition made of TMP, SGWD, and LYS is the interior of the triangle (AA'B'), representing the 100 LYS pulp: A, the 100 TMP: A', and the 100 SGWD pulp: B'.

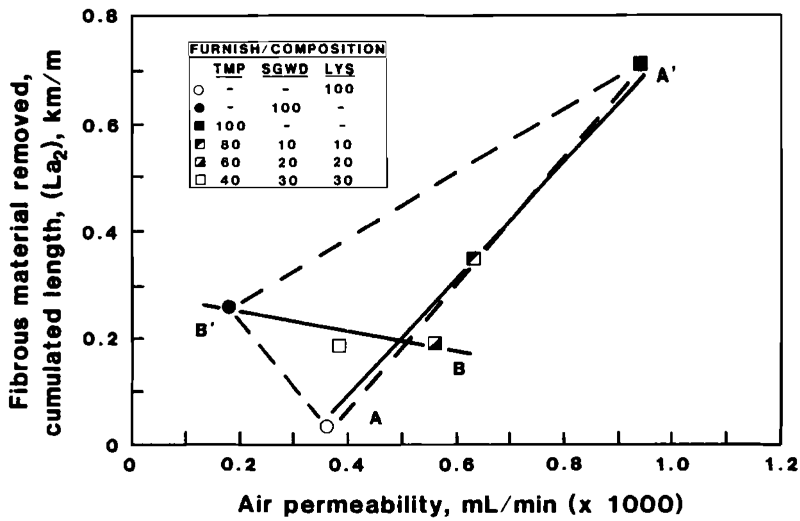

Figure 6 Cumulated fibre length removed per printed unit area as a function of the air permeability (P20) of the BHM papers.

The morphological similitude between **Figure 6**, representing an interaction graph between the fibre network structure and the cumulated length of fibres removed during printing, and **Figure 4**, representing an interaction graph between the number of fibrous elements and the fibres origin removed during printing, supports the same conclusions as far as the relative importance of long TMP fibres and SGWD fines are concerned. In **Figure 6**, it can be shown that the number of long TMP fibres being removed increases along the AA' axis, in the direction of the 100 TMP point A' representing a maximum in fibre removal. Similarly, the SGWD fines increasess along the AB' axis, in the direction of the 100 SGWD pulp point B'. For these pulps, the results clearly indicate that fibre removal is enhanced by TMP which contains poorly fibrillated, stiff, long fibres. Inversely, fibre removal is reduced by the presence of a large number of well fibrillated fine material, as present in the SGWD pulp. As seen before, the SGWD pulp is quite advantageous in increasing the resistance to surface debonding.

The Surface Bonding Potential of BHM Randomly Oriented Papers as Measured in Constant-Mode Printing (modified Varkaus)

The IGT pick test, performed in accelerated-mode printing, permits the evaluation of a range of printing speeds in a single printing experiment. Previous analysis of the IGT pick test results demonstrated the test usefulness when extensively interpreted. However, printing in an accelerated-mode as little practical interest as, outside the press start-up, printing is mostly done at constant speed. Furthermore, ink flow in the printing nip, recently proposed **[Mangin, 1988, Mangin-Silvy, 1992]** as a main contributor to fibre removal, has only been described for constant speed but not in accelerated-mode printing. It is therefore presently impossible to calculate the debonding forces acting at the paper surface during accelerated-mode printing. The forces are due to ink flow velocity in the paper surface pores. Furthermore, we have shown elsewhere **[Mangin et al, 1990]** that accelerated-mode printing imparts a surface shear to the paper surface that also contributes to fibre debonding.

Accordingly, due to both theoretical and practical considerations, the BHM paper surface resistance to fibre debonding has been evaluated in constant-speed printing using a modified version of the Varkaus test.

Analysis of the Modified Varkaus Test The mass balance, the weight F, the number Na, the average length, L_1 or L_2, and the cumulated length, La_1 or La_2, of the fibrous material removed during printing of the BHM sheets in the modified Varkaus test are presented in **Table 6**. The mass balance is $(Y - F)$. It is the difference between the ink transferred to the paper and the fibres transferred back to the printing plate.

Table 6 shows that the standard Varkaus test is inherently complex to analyze. For most samples, the mass balance decreases as a function of the printing speed; but not for the 100 TMP sample. In the Varkaus test, no provision is made for variations in ink transfer due to various printing conditions or paper properties. We have shown elsewhere **[De Grâce/Mangin, 1984]** that, for both porous medium such as newsprint, and impervious synthetic medium such as polypropylene, the ink transferred to the paper Y decreases when printing speed increases. For very porous papers, such as BHM sheets, the ink transfer, at a constant ink weight on the printing plate, even goes through a minimum as a function of the printing speed.

Before the ink transfer minimum, a decrease in mass balance might be due to both a decrease in ink transfer (Y) or an increase in fibre removal (F). After the minimum, the two effects compete as both ink transfer and fibre removal increase. The 100 TMP paper has a very open structure, indicated by a high air permeability (940 $mL.min^{-1}$). It can be deducted that the ink transfer predominates over fibre removal; i.e. the mass balance presents a minimum.

Table 6. Fibre Removal at Constant Speed Printing Performed on British Handsheet Randomly-Oriented Papers: Varkaus Test Data.

Speed, $m.s^{-1}$	Na $x10^{-4}$	Mass Balance, mg Varkaus* Y - F	Fibre** F	Fibre Length mm L_1	L_2	Cumulated Length, $km.m^{-2}$ La_1	La_2
100 TMP							
3.0	117.7	9.9	9.9	0.79	1.47	0.924	1.733
4.6	100.9	4.2	13.9	0.81	1.47	0.812	1.486
6.0	245.1	10.2	17.1	0.80	1.62	1.959	3.976
100 SGWD							
3.0	25.6	15.2	0.98	0.37	0.92	0.090	0.225
4.6	25.8	14.9	1.27	0.47	1.16	0.12	0.299
6.0	64.2	13.1	4.61	0.51	1.05	0.329	0.673
100 LYS							
3.0	23.7	12.2	0.73	0.31	0.74	0.074	0.177
4.6	27.7	12.4	0.22	0.32	0.70	0.089	0.194
6.0	18.4	10.7	0.93	0.47	0.93	0.086	0.171
80 TMP							
3.0	76.5	11.1	12.1	0.67	1.32	0.513	1.011
4.6	137.2	10.7	9.88	0.76	1.42	1.039	1.941
6.0	266.3	6.6	16.6	0.78	1.58	2.079	4.200
60 TMP							
3.0	67.0	12.9	3.12	0.69	1.32	0.462	0.866
4.6	48.2	10.1	8.65	0.74	1.54	0.355	0.741
6.0	185.5	6.5	14.8	0.70	1.49	1.298	2.758
40 TMP							
3.0	44.4	13.2	2.08	0.48	1.05	0.213	0.465
4.6	45.9	10.7	2.76	0.60	1.31	0.276	0.600
6.0	134.2	10.0	8.18	0.64	1.38	0.858	1.856

*Na, L_1, L_2, La_1, La_2 as previous Table 5; * average coefficient of variation is 2.8% for an average ink weight on the printing plate of 4.972 $g.m^{-2}$ (± 1.1%); ** fibre weight cumulated on 4 printing plates and 3 overprints; i.e. 0.0215 m^2.*

Another apparent problem of the standard Varkaus analysis relates to the fact that the SGWD pulp appears even stronger than the chemical LYS pulp. However, previous analysis of the IGT pick test had clearly shown that LYS pulp was the strongest; to the point that it served as reference point for low fibre removal. The low air permeability (183 $mL.min^{-1}$) of 100% SGWD sheets, when compared to the air permeability of the 100% LYS sheets (363 $mL.min^{-1}$), indicates that the SGWD papers have a surface structure more closed than the structure of LYS papers. We therefore assume the following relation for ink transfer:

$$Y(SGWD) > Y(LYS) \quad (1)$$

Data in **Table 6** verify Equation 1, and

$$Y\ (SGWD)\ -\ Y\ (LYS)\ >\ F\ (SGWD)\ -\ F\ (LYS)\ >\ 0 \quad (2)$$

or

$$Y\ (SGWD)\ -\ F\ (SGWD)\ >\ Y\ (LYS)\ -F\ (LYS) \quad (3)$$

Equations 1-3 suggest that, when comparing chemical and mechanical pulps, the maximum shown by the 100 SGWD pulp is mainly related to a maximum in ink transfer and not to a maximum in resistance to fibre removal.

In the modified version of the Varkaus test, printing is performed with a clear medium, soluble in petroleum ether. It is therefore feasible to separate the fibre component from the ink component. Considering fibre removal phenomena, the test is improved and the analysis of the results simplified. **Figure 7** shows the fibre weight removed from the paper surface during printing in the modified Varkaus test, for the 3 printing speeds, as a function of the specific surface of the pulp fibres. Except for the SGWD pulp, the mass of fibrous material removed during printing increases as a function of the specific surface of the pulp fibres and as a function of the printing speed. As previously found in the analysis of the IGT pick test performed in accelerated-mode printing, the 100 SGWD pulp shows a rather good resistance to surface deterioration during printing, quite similar to the chemical 100 LYS pulp. However, there is a fundamental difference between the two pulps as far as the effect of speed is concerned. In the range of printing speeds evaluated, the resistance to fibre removal of the 100 LYS is almost independent of the printing speed. This is not the case for the 100 SGWD. The fibre weight removed during printing increases abruptly from printing speed 4.6 m/s^{-1} to 6.0 $m.s^{-1}$. This effect, related to the removal of a larger number of fibres, indicates the existence of a debonding threshold for the mechanical SGWD pulp. From 4.6 $m.s^{-1}$ to 6.0 $m.s^{-1}$, the weighted average length L_2 decreases; while both the number and the cumulated length La_2 of fibres removed increase drastically. The conclusion concurs with the analysis of the relative influence of TMP fibres and SGWD fines for the inter-relation graphs obtained with IGT pick testing.

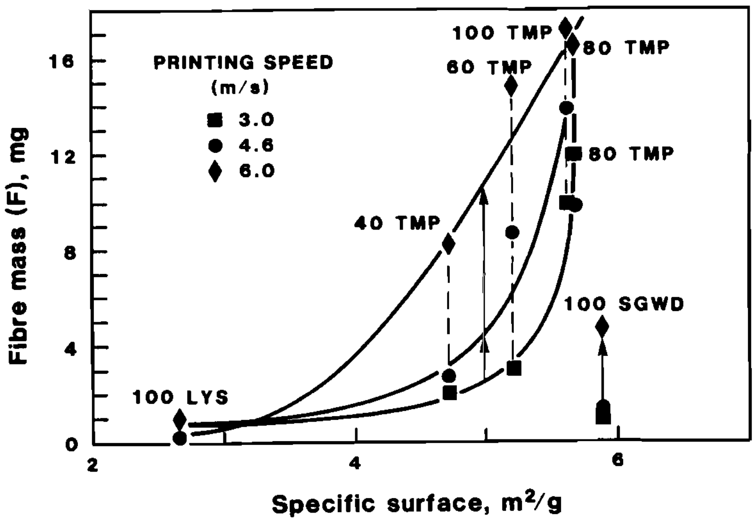

Figure 7 Fibre weight removed from the surface of BHM papers in the modified Varkaus test as a function of the specific surface of the pulp fibres. Printing ink is a 12% resins solution in clear mineral oil.

In essence, the removed fibre mass F comprises an integration of the fibres by weighing. It is the product of the fibre coarseness, or weight per unit length w_i, by the cumulated length of fibres removed from the paper surface during printing. Considering the arithmetic fibre length L_1:

$$La_1 = Na\ L_1 \tag{4}$$

and

$$F = w_i\ Na\ L_1 \tag{5}$$

with

Na number of fibrous elements removed per printed unit area, in mm,

La_1 cumulated length of fibrous elements removed per printed unit area, in $km.m^{-2}$.

The fibre coarseness of fibrous material removed from both the stone groundwood and thermomechanical pulps of identical wood species are approximately equal. From **Table 6**, the weight per unit length has been evaluated at 5.6 10^{-6} g.cm^{-1} ($\pm$ 1.5 10^{-6} g.cm^{-1}). A comparison with the coarseness of softwood mechanical pulps **[Bichard/Scudamore, 1988]**, ranging from 2.5 to 3.0 10^{-6} g.m^{-1}, shows that the coarseness values of removed fibrous material is almost twice as large.
The hypothesis that the removed fibrous material has a higher lignin content than the whole pulp could not be verified. Lignin content analysis is quite tedious and requires a large amount of fibrous material. Due to the minute quantities of fibrous material available for the measure, the differences between the various lignin contents were about as large as the experimental error of the measure. However, a microscopic evaluation of the fibrous material removed showed a large proportion of fibres bundles comprising two to three joined fibres. Although qualitative, the observation explains the high values of fibre coarseness. The Kajaani FS-100 fibre analyzer measures the length of fibres but not their thickness. The fibre mass was evaluated separately by weighing. In essence, a shive composed of two joined fibres has the same unit length but double mass of a single fibre.

Average Fibre Length. **Figure 8** shows that, at the exception of the SGWD sample, the average length of removed fibres increases linearly, for all 3 printing speeds, as a function of the specific surface S_w of the pulp fibres. The reasons for excluding the 100 SGWD pulp from the regression analysis have been explained previously. Considering the weighed average fibre length, we propose the following relationship:

$$L_2 = a_0 + a_1 Sw \tag{6}$$

The main explanation for the increase in fibre length relates to the removal of long TMP fibres, increasing with the TMP content of the pulp furnish. A microscopic analysis showed that the fibrous material removed at 6.0 m.s^{-1} contained a large proportion of un-fibrillated long TMP fibres.

Cumulated Fibre Length **Figure 9** shows the cumulated fibre length of fibrous material removed from the paper surface during the constant-speed printing as a function of the specific surface of the pulp fibres. A similar graph (not shown here) was obtained with the number of fibres removed. At the exclusion of the 100 SGWD pulp, both graphs present a quadratic relationship between either the number or the cumulated surface and the specific surface of the pulp fibres.

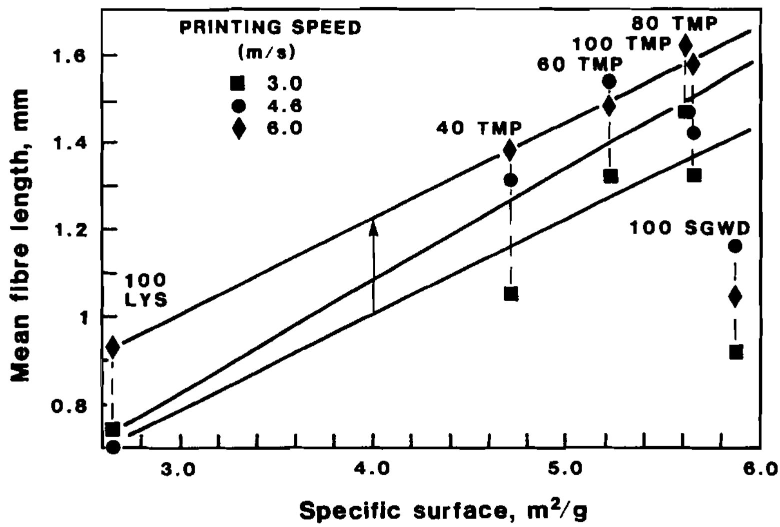

Figure 8 Average fibre length of fibres removed from the surface of BHM papers in the modified Varkaus test as a function of the specific surface of the pulp fibres.

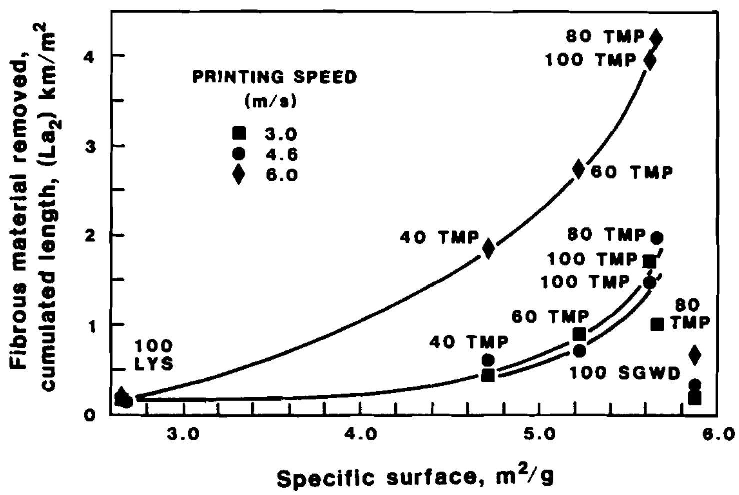

Figure 9 Cumulated length of fibres removed from the surface of BHM papers in the modified Varkaus test as a function of the specific surface of the pulp fibres.

The quadratic relationship is verified with a determination coefficient $r^2 > 0.87$. We propose the following symbolic relationships:

$$Na = f_1 \ (Sw^2) \qquad (7)$$

and

$$La_2 = f_2 \ (Sw^2) \qquad (8)$$

In addition to the quadratic relationships, the graphs include three important characteristics. First, the 80 TMP (that includes 10% SGWD and 10% LYS) presents a maximum in fibre removal from both the number and the cumulated length standpoints. Although marginally larger than the 100 TMP sample, the fibre removal potential is coherent with the marginal increase in specific surface. It implies that the linting potential of the 80 TMP sample is higher than any other SGWD-LYS-TMP furnish combination. Tests performed on a pilot offset press confirmed the tendency **[Mangin, 1988]**.

Second, although the quadratic relationships are not a function of the printing speed, a debonding threshold exists between 4.6 and 6.0 $m.s^{-1}$. A speed increase from 3.0 to 4.6 only shows a marginal increase in fibre removal. This might explain the controversy as far as the printing speed effects are concerned. Some authors seeing either little or no effect of speed on lint accumulation on offset blankets **[Mangin, 1991]**.

Third, the 100 SGWD sample has a higher resistance to surface fibre removal than predicted by the specific surface analysis. This confirms previous analysis using the accelerated-mode printing. However, this also means that the specific surface is not sufficient, considered alone, to explain the linting propensity or fibre removal potential of the papers, other parameters should be considered.

Bonding strength and Fibre Removal The peculiar characteristics of the 80 TMP and 100 SGWD samples can be further explained when considering the internal Scott bond and the structural properties of the paper sheets. As shown in **Figure 10**, the surface deterioration of BHM papers, as evaluated by the cumulated length of fibres removed per printed unit area decreases as a function of the internal bond strength (LI) between fibres. We propose the following relationship:

$$La_2 = f_3 \ (LI^{-1}) \qquad (9)$$

Equation 9 relates a general 'pulp' strength parameter, the internal bond Scott, to the surface fibre removal. As such, the 100% stone groundwood pulp sample follows the proposed relationship. As seen previously, the effect of speed is linked to a threshold in debonding energy that occurs between 4.6 and 6.0 m.s^{-1}. The fibre removal curves for the low speeds, 3.0 and 4.6 m.$^{-1}$ are not statistically different. The fibre removal curve at 6.0 m.s^{-1} presents much higher surface deterioration levels. For the highest speed curve, the average length of fibre removed is significantly higher (**Figure 8**). Finally, all fibre removal curves decay asymptotically to reach a minimum at high bonding levels. The minimum value is illustrated by the 100% chemical pulp (LYS).

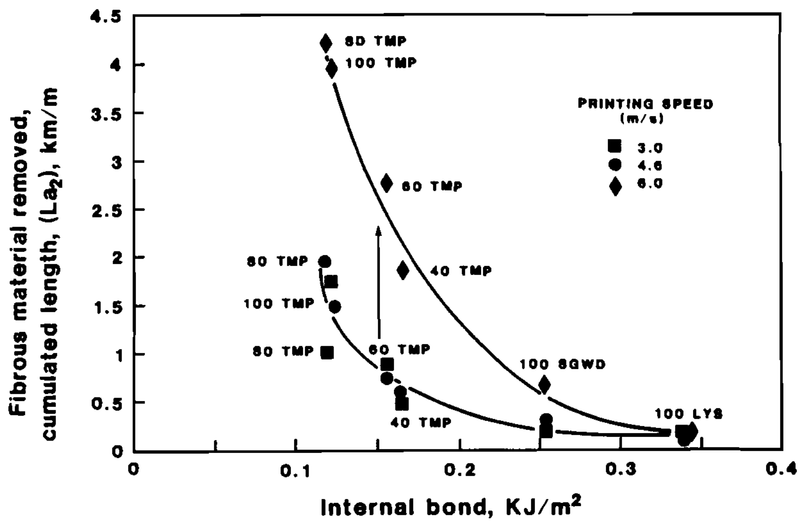

Figure 10 Cumulated length of fibres removed from the surface of BHM papers in the modified Varkaus test as a function of the internal Scott bond.

Paper Structure and Fibre Removal **Figure 11** shows the cumulated fibre length of fibres removed per printed unit area as a function of the air permeability of the BHM sheets. In general, the more open structures, which have a higher air permeability, present the highest values of fibre removal. However, it should be emphasized that the structural component in fibre removal should be analyzed concomitantly with the previously evaluated parameters, such as bonding strength and specific surface. In the case of the 80 TMP paper, with a furnish composition of 80% TMP, 10% SGWD, and 10% LYS, the more porous, open structure seems to have a negative effect on fibre removal. When comparing the 100 LYS to the 100 SGWD, at low printing speeds, the open structure seems to have no effect. In all cases, the differences related to the paper structure are comparatively larger at the highest printing speed (6.0 m.s^{-1}). From these observations, we conclude that, because of the porous structure of the paper, ink flow should be considered in fibre removal mechanisms during printing. Ink flow should, of course, be considered in addition to the well-known ink tack that also transfers a force to the paper surface.

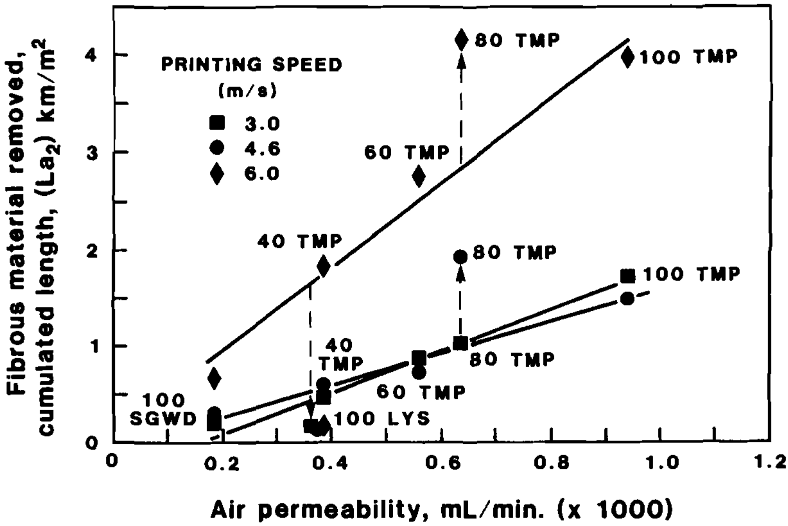

Figure 11 Cumulated length of fibres removed from the surface of BHM papers in the modified Varkaus test as a function of the air permeability (P20) of the BHM papers.

Therefore, fibre removal in a printing nip is also a function of a structure parameter S. Here, the structure parameter is illustrated by the air permeability. It results in a linear relationship. The structure parameter should be used to characterize the ink flow behaviour in the paper porous structure [**Mangin, 1988, Mangin/Silvy, 1990**]. We propose the following relationship:

$$La_2 = f_4 \ (S) \tag{10}$$

General Symbolic Relation From this study of printing performed at various printing speeds, we propose that the fibre removal in the printing nip is a - yet unknown - function of a parameter related to the length distribution of the pulp fibres, mainly the low-length tail, the specific surface of the pulp fibres S_w, a parameter that provides some indication of the inter-fibres bonding strength LI, or better, a parameter that would characterize the bond strength distribution of the surface fibres, and a structure parameter that characterize the ink flow in the printing nip. A general, also not complete, relationship is proposed such as:

$$La_2 = f_5\ (Sw,\ Sw^2,\ LI^{-1}) \qquad (11)$$

PRELIMINARY CONCLUSIONS

From a simple laboratory study of fibre removal in the printing nip, some preliminary conclusions have been drawn that pertain to the understanding of the linting propensity of papers. The conclusions both from accelerated-mode printing, as in the IGT pick test, and constant-speed printing, as in the Varkaus test, are coherent.

First, no single pulp or paper property, considered alone, is sufficient to explain or understand the complexity of fibre removal in the printing nip. Although not exhaustive, the study has shown that bonding strength, specific surface, and the paper structure influence fibre removal in the printing nip.

Second, symbolic relationships have been proposed that describe the various expected interactions. The influence of the specific surface S_w of the pulp fibres is quadratic. The average fibre length is proportional to S_w, and the cumulated fibre length is proportional to S_w^2. Fibre removal is inversely proportional to the bonding strength.

Third, as structure affects fibre removal through ink transfer, ink flow in the printing nip should be considered in any general equation that describes fibre removal. Ink flow does not preclude ink tack effects.

Fourth, because of the interactions between the various paper properties that control fibre removal, any general equation that describes the phenomena in terms of paper properties is bound to be non-linear.

Fifth, a threshold in debonding level has clearly been establish. Below this level, fibrous material removal is almost independent of the printing speed. The threshold level is related to true fibre debonding or fibre picking.

REFERENCES

Bichard, W. and Scudamore, P.

1988 An evaluation of the comparative performance of the Kajaani FS-100 and FS-200 fibre length analyzers, MR 135, Paprican, Pointe Claire, Can.

De Grâce, J.H. and Mangin, P.J.

1984 A mechanistic approach to ink transfer. Part I: Effect of substrates properties and press conditions, Adv. Printing Science and Technology, Vol 17, W.H. Banks Ed., Pentech Press, London, 312-332.

Hughes, F.P.

1966 A definitive test for the linting propensity of web offset newsprint, TAPPI 49(10), 46A-49A.

Karttunen, S.

1975 Printability and linting of offset newsprint, Graphic Arts in Finland 4(1), 18-34.

Kuvaja, A.M.

1972 An empirical method for testing the surface strength of offset newsprint, Paperi ja Puu, 54(12), 1-5.

Lindem, P.E. and Moller, K.

1992 The "Dagbladet full-scale printing trials: Linting in four-colour offset printing, IPGAC Proc., 141-163.

Mangin, P.J.

1987 A review of the evaluation of the offset linting propensity of paper, TAGA Proc., 397-442.

1988 Etude de la déstructuration de la surface du papier en zone d'impression offset, PhD Thesis, INPG, Grenoble, France, 310 pp.

1989 Can laboratory test predict offset linting propensity of newsprint? CPPA/TS Annual Mtg, Preprints B387.

1991 A critical review of the effects of printing parameters on the linting propensity of paper, JPPS 17(5): J156-J163.

1992 La difficile évaluation du peluchage en impression offset, Les Papetières du Québec, 2(4): 1-5.

Mangin, P.J., Aspler, J.S., and De Grâce, J.H.

1985 A papermaker's approach to the analysis of paper printing characteristics, TAGA Proc., 359-381.

Mangin, P.J. and Silvy, J.

1990 Surface pore structure, ink flow, and fibre removal during printing, Intern. Paper Physics Seminar, Kalamazoo, MI., Abstract only.

Mangin, P.J., Silvy, J., and De Grâce, J.H.

1990 Offset linting studies: Part II. Further considerations to linting theories, IPGAC Proc., Vancouver, B.C., Can., Preprints 109-119.

Mangin, P.J. and Dalphond, J.E.

1992 A novel approach to evaluate the linting propensity of newsprint. Part 1: Background and test procedure, Pulp&Paper Can., 93(12), T409-T414.

1993 A novel approach to evaluate the linting propensity of newsprint. Part 2: Case studies, Pulp&Paper Can., 94(1): T5-T10.

Wood, J.R., and Karnis, A.

1990 Linting propensity of mechanical pulps, Preprints, 5th International Printing and Graphic Arts Conf., Vancouver, B.C., 59-71.

Wood, J.R., Imada, S.E., Beaulieu, S., and Kerr, R.B.

1993 Reduction of offset linting - A comparison of six mills, PPR 989, Paprican, Pointe Claire, Canada.