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UNCOATED PAPER SURFACE FOR COLDSET WEB OFFSET PRINTING. SET-OFF STUDIES

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ABSTRACT

Four-colour printing of newspapers has grown strongly during the past ten years, demanding better print quality. To achieve this with rough uncoated newsprint, more ink has to be applied on the surface of the paper. However, the use of more ink tends to cause greater smearing problems. Therefore, among the various types of smearing, such as rub-off and smearing of printing press elements, set-off has become a more prominent problem impairing print quality. It takes place e.g. in the folder of the printing press and in other post-press operations when the sheets are pressed against each other immediately after printing and wet ink is transferred to the facing sheet.

This study examines set-off in newspaper printing and its relation to newsprint properties and other printing parameters, consisting of a review of the literature related to the subject, a theoretical discussion of open questions and a set-off process analysis. Laboratory printing tests (Prüfbau) with laboratory-made paper and ink samples and commercial newsprint and newsink samples were carried out to shed more light on the questions, which were not fully covered in the literature and theoretical discussion. In addition, the surface of newsprint, the structure of the offset blanket, the ink penetration and its location on the paper surface, and set-off prints were studied with microscopic methods. Because set-off has its roots in the printing process itself, ink transfer and ink setting and the situations where set-off is created were also examined in the study. Two main targets were set for this work: to define the optimum surface characteristics for uncoated newsprint in newspaper printing with the coldset web offset (CSWO) method and to gain a better insight into the set-off phenomenon.

In CSWO printing, ink is transferred from the offset rubber blanket to the paper aided by the pressure in the printing nip. The ink covers the rough surface of newsprint, though not completely. The compressibility and conformability of the blanket and the compressibility of the newsprint surface improve the ink coverage. At the outlet of the printing nip the ink film splits but only in the area where the ink film has been in contact with the newsprint surface. In single-colour printing, the penetration of ink into the interior of the paper, which is caused by the pressure in the printing nip, is insignificant. In contrast, in multi-colour printing, the ink layer printed later pushes the previously printed ink deeper into the voids of the paper surface and even under the surface fibres.

Set-off decreases rapidly during the first seconds after printing, but the decrease then slows down. Besides the delay time, the most important parameters of CSWO printing for set-off are: the amount of ink transferred to the paper, the pressure in the set-off situation and the type of paper (newsprint made of deinked pulp (DIP) or virgin mechanical pulp at the same roughness). The chemical pulp in DIP-based newsprint reduces the compressibility of the paper surface, which means less contact between the ink on the paper and the facing sheet under the pressure exerted by the pressing elements in the set-off situation. This explains the lower set-off values of DIP-based newsprint in comparison with newsprint made of virgin pulp. Another but less effective parameter is the printing nip pressure. A higher pressure gives better ink coverage,

reducing the ink requirement for the desired print density. It also distributes the ink deeper into the roughness profile, resulting in less set-off.

Ink setting decreases set-off. Ink setting is more likely the result of solvent separation from the ink layer rather than total-ink absorption. For this reason ink setting is defined by the change of the set-off during the delay time, and it is the derivative of the set-off equation created in this study including also the solvent release parameter from the ink layer. Ink setting can be improved by adding filler to the pulp. The amount of loading is more important than the type of filler, i.e. whether its particles are platy or spherical. A longer delay time from printing to a set-off situation would reduce set-off, though the delay time cannot usually be changed in normal newspaper printing.

Set-off can be reduced by using less ink, higher printing nip pressure, lower pressure in the folder and in other set-off situations related to post-press operations, and DIP-based newsprint calendered to relatively high roughness.

The most important properties of uncoated newsprint for set-off in CSWO printing are: optimised roughness in relation to print quality (evenness of solid print and contrast in dark tones) and set-off, low surface compressibility, high specific surface area, good absorption ability of the fines area (high proportion of fine pores below one micrometer) and uniform formation (no high-density calendering spots). However, the runnability of the paper on the printing press must not be sacrificed.

PREFACE

The thesis has carried out at UPM-Kymmene, Valkeakoski Research Centre during 2000-03. Some experimental work has been done earlier. The model inks and ink analysis were produced by Sicpa Oy, Tampere.

For the good advices of the reporting, I express my gratitude to the supervisor of the thesis professor Hannu Paulapuro.

I would like to thank the personnel of VRC laboratory who did pulp and paper work and testing and also the microscope pictures. Special thanks to Jussi Jäättelä, and Kyösti Haapoja who handled the subject as master's thesis workers. I also thank to all the people of UPM-Kymmene who had made this work possible not the least for the project group members and my dear friend Roger Price who has read the text and who has given good linguistic advices. Specifically, I would like to thank the personnel of Sicpa Oy and Markku Merilahti and Heikki Hauhia for the very kind co-operation with the printing inks.

Finally, I would like to dedicate this experiment for my children Päivi, Jaakko, Mikko, Ulla and Pertti. To work is a real blessing and a sound function in our live. Sometimes it is hard; sometimes it can also be fun.

Valkeakoski June 2004

Seppo Särelä

Cover: The picture (UPM-Kymmene, VRC) is a 4-colour rotogravure printed microtome cross section of a SC grade.

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Nomenclature

BEI	Backscatter electron imaging
BET	Brunner, Emnet and Teller (specific surface area by nitrogen gas adsorption method)
CSWO	Cold set web offset printing method of paper
CIC	Common impression cylinder
CLSM	Confocal laser scanning microscope
CMYK	Cyan, magenta, yellow, black (key) ink sequence
CTMP	Chemi-termomechanical pulp
DIP	Deinked paper stock pulp
EDANA	European Disposables and Nonwovens Association
ETA	The resultant signal-to-noise ratio in Taguchi analysis
GFL	Grafiska Forsknings Laboratoriet
GW	Ground wood pulp
HUT	Helsinki University of Technology
HSWO	Heatset web offset
IBAS	Kontron IBAS2 image analyser
IFRA	INCA-FIEJ Research Association
IGT	IGT laboratory printability tester
IPA	Isopropyl alcohol
KAM	Kontact Antail Meter
KCL	The Finnish Pulp and Paper Research Institute
LWC	Light weight coated paper grade
LOG	Base 10 logarithm
LN, ln	Natural logarithm
MFC	Machine finished coated paper
MFS	Machine finished speciality paper
NC	North Carolina
NEWS	Newsprint
P_{av}	Average pressure
PGW	Pressure ground wood pulp
PPS S	Parker Print Surf air-leak roughness meter with soft backing
PPST	Pira printing smoothness tester
PT	Print through
Ref., ref.	Reference
RMS, R_{RMS}	Root mean square deviation of surface height
RTF	Roller top of former
RTS^{TM}	Low retention-high temperature-high speed (TMP refining technology)
SEM	Scanning electron microscope
SEI	Secondary electron imaging
SO	Set-off, smearing of CSWO printed paper
$SO_{2.5}$	Set-off measured 2.5 seconds after printing
SO_{60}	Set-off measured 60 seconds after printing
ST	Strike-through
TAGA	Technical Association of Graphic Arts
TMP	Thermo mechanical pulp
UBM	Laser profilometer
UPM	United Paper Mills
VRC	UPM-Kymmene, Valkeakoski Research Centre
VTT	Technical Research Centre of Finland
W-F	Walker and Fetsko

Symbols

D	Print density
d	Diameter
g	Gravitational acceleration
g/m2	Grams per square meter
H, h	Height
Hg	Mercury
l	Length
L	The half of the fibre width
N	Number of observations
p	Pressure, probability
r	Linear correlation factor, or radius
Re	Reynold’s number
T	Temperature (absolute scale)
t	Time
u	Speed
V	Volume
η (eta)	Viscosity
φ (phii)	Contact angle
γ (gamma)	Surface tension
ρ (ro)	Specific density

CONTENTS

1 INTRODUCTION

1.1 Background

A large majority of newspapers and their supplements along with some books and newspaper type magazines are printed by the coldset web offset method (CSWO). Standard newsprint is largely used but many special uncoated newsprint grades (MFS) are on the market. Only few coated grades can be printed in coldset offset because of the smearing of non-drying ink.

Colour printing is more and more common, which emphasises good print quality (Figure 1) /1/. This has increased ink volume on paper and this also has made smearing more critical. Paper development has decreased consumption of raw materials, and increased the use of filler and recycled pulp (DIP) for environmental and economical reasons leading to lower grammage and different structure of paper (Figure 2). Also, newsprint used today is rougher than that used at the beginning of the last decade /2/.

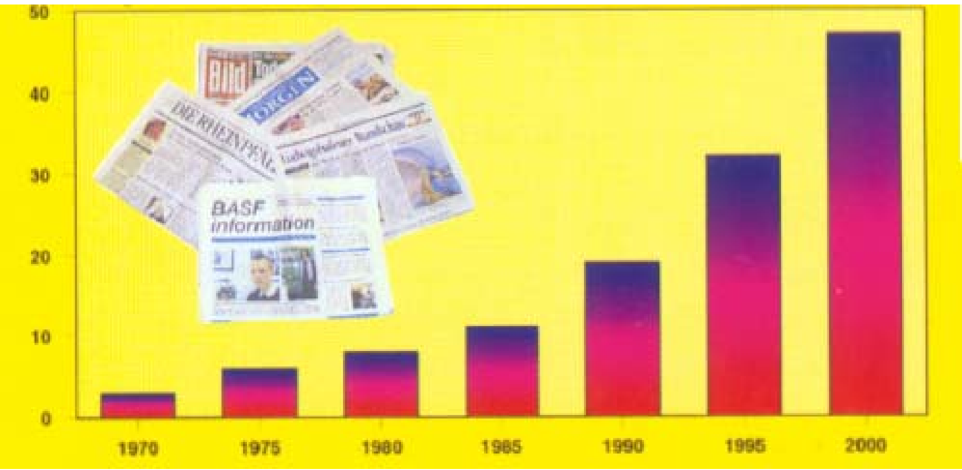

Figure 1. Development of colour printed newspapers as percentage in Europe /1/.

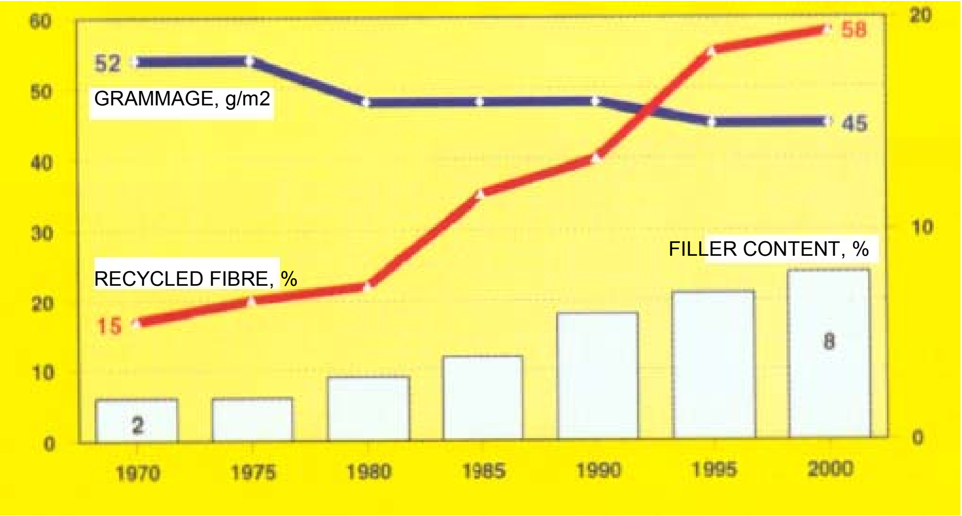

Figure 2. Trends of newsprint in Europe /1/.

DIP based newsprint grades have been positively found to smear less than those based on virgin fibres /3, 4, 5/. It is also said that in all cases, the ink/paper combination can be optimised, also for different types of paper /5/. However, the development towards 100% DIP newsprint has also been said to cause runnability problems, worse dimension stability, and lower web and surface strength /1/. Smearing deteriorates print quality by giving a dirty appearance to printed matter. However, the characteristic properties of paper surfaces especially in the case of smearing in the CSWO process are not very well known.

1.2 CSWO printing process

Drawings of the most common types of the CSWO printing presses are presented in Figure 3. The blanket-to-blanket and the satellite presses are the main types, and the horizontal and the vertical designs of both types are in the use.

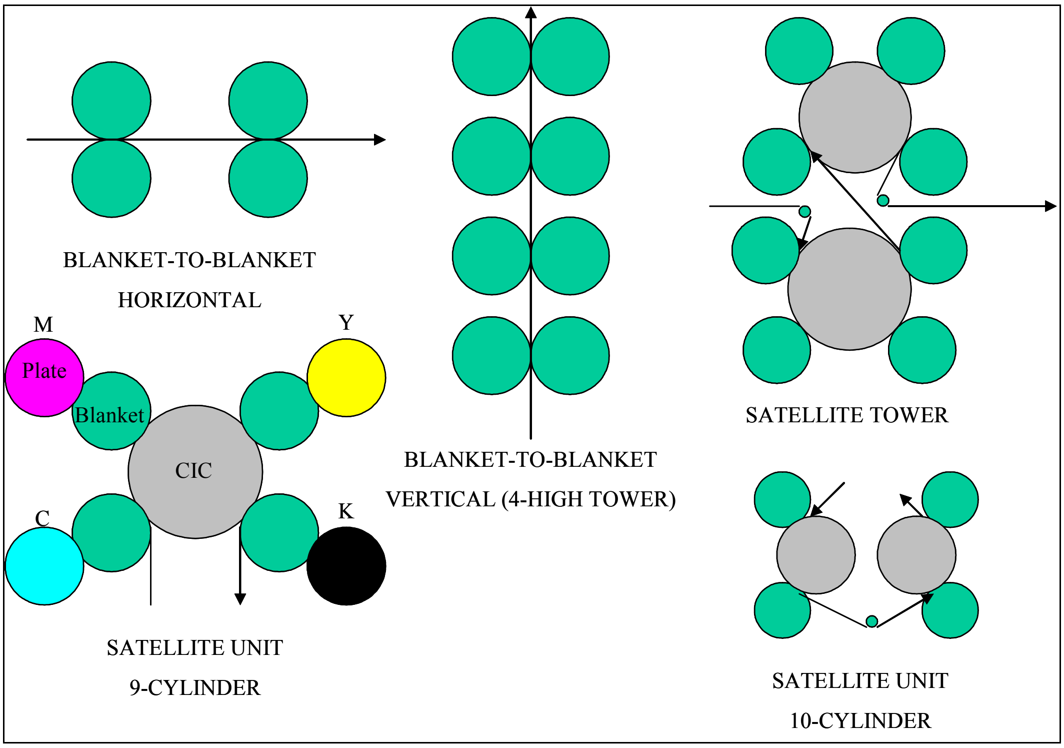

Figure 3. Common types of CSWO printing units. CIC is Common Impression Cylinder. A very commonly used ink sequence is cyan-magenta-yellow-black (CMYK). K stands for 'key'.

The machine design for a newspaper depends on the number of pages, especially coloured pages and the page format (Euro-format, tabloid etc.). A newspaper can be printed from one or several reelstands. Older presses especially can contain different types of printing units because the newspapers have increased colours and coloured pages step by step, instead of installing a complete new machine at once. So, there is not one standard printing press design for newspapers.

1.3 Smearing in CSWO printing

A normal CSWO printing press has no drying unit for inks. The inks, often called newsinks, do not include drying components for polymerisation by oxidation, either. Instead, the inks set in time after printing. The non-set ink can smear touching elements of a printing machine e.g.

transfer rolls and turning bars, and also the facing paper sheet /6/. The terms, rub-off, second impression set-off, and set-off describe more exactly the type of smearing.

Rub-off is abrading of a printed surface and it is normally tested e.g. after 4 hours, or like IFRA /7/ proposed, after 24 hours, when the printed ink has already set. The test should simulate the rubbing of fingers.

The second impression set-off can take place especially in the satellite printing units /6/. On the first printing unit, all four colours are printed on one side of paper and then the paper web is fed into the second printing unit. The first side print is still wet and ink with paper based material can adhere onto the common impression cylinder (CIC, see Figure 3). If the build-up grows cumulatively it will disturb the print quality of the second side of paper, and it can even destroy the offset blankets.

2 DEFINITION OF SET-OFF IN CSWO PROCESS

Set-off is one of the biggest problems limiting the development of CSWO print quality. In Figure 4, we illustrate the way, which set-off takes place. A freshly printed sheet is pressed against a facing sheet. Wet ink is transferred by the pressure onto the surface of the other sheet that is also called ‘counter' paper, or ‘facing' paper, or recipient paper /2, 8/.[1]

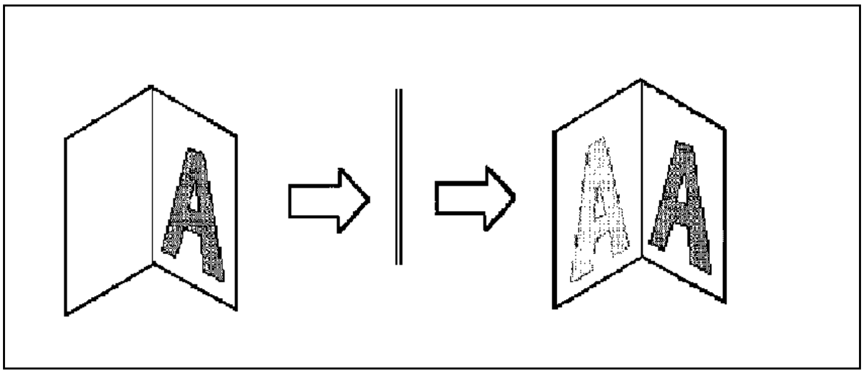

Figure 4. Set-off phenomenon. Set-off takes place when a printed sheet with wet ink is pressed against another sheet. A part of the wet ink has transferred onto the facing page /2, 8/.

In Figure 5, newspaper printing and post press handling are presented in a schematic way. In multiple web printing, often, the first time the printed webs touch with each other is on the Roller Top of Former (RTF) just before the folder (Figure 6). The pressure in this place is created by web tension.

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[1] In this work, 'facing' paper is used for the production scale printing and 'counter' paper for laboratory scale test printing.

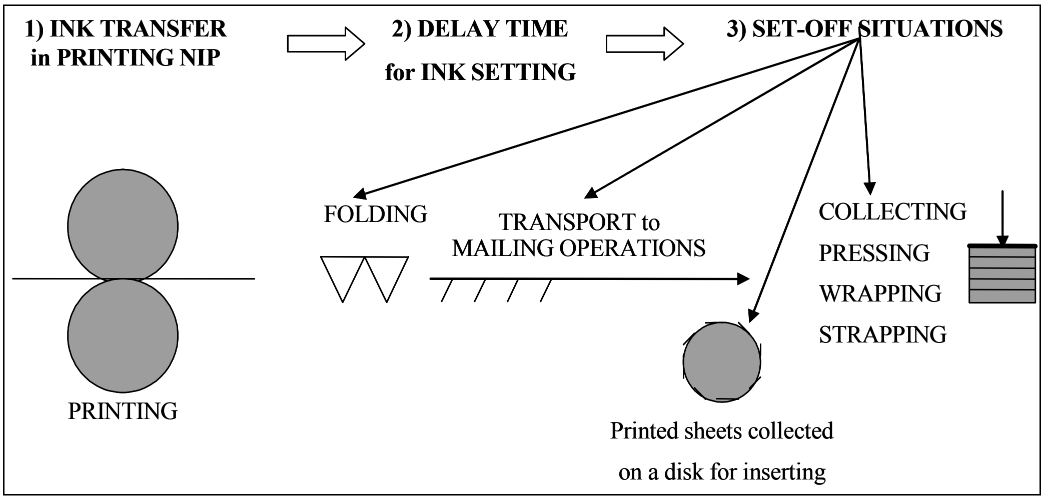

Figure 5. Newspaper printing, folding, and handling for mailing.

The delay time from a printing nip to the folder varies ca. from one to a few seconds depending on the printing machine design and the running speed. In Figure 6, one can see an example of the distances from the printing units to the folder.

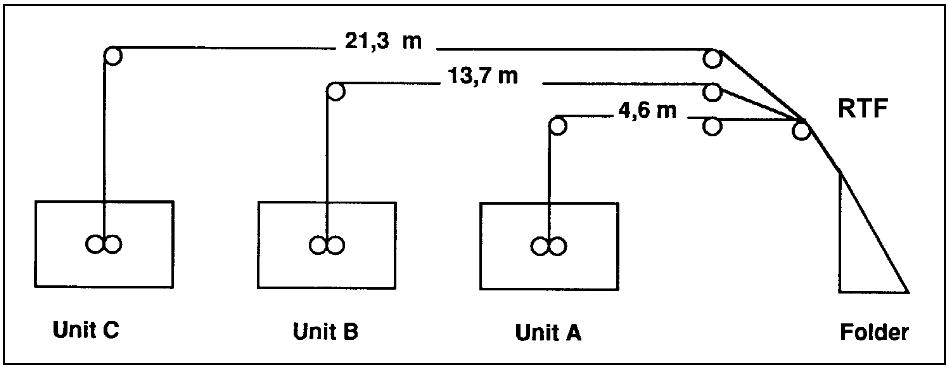

Figure 6. An example of the distances between the printing units and the folder. RTF stands for Roller Top of Former. /7/

The folder has several elements, which squeeze sheets against each other causing set-off, e.g. nipping rollers and jaw cylinders. High pressure takes place especially in the fold of the paper set, where one can often see set-off. The pressure needed for folding depends on e.g. the paper grade and the number of pages.

Transportation of the ready newspapers from the folder to mailing operations is usually done by conveyers with grippers. Grippers can also cause set-off by pressing some parts of the folded newspaper, one or two samples. The grippers themselves can become smeared with ink.

During normal newspaper printing the newspapers are transported from the printing machine directly to the mailing operations, where a certain number of newspapers are collected, pressed down, wrapped, and strapped as a tight package. Many advertisements are distributed to the public with newspapers as inserts. To put an insert into the space between the pages of a newspaper is called ‘inserting’. Because the inserts are often printed separately from the newspaper itself, the printed inserts are collected on storage discs to await inserting. The inserts are tied on the disc with narrow plastic belts, one or two, with the high pressure against the sheets. In practice, we often see set-off under the belt.

Set-off can take place at all the points where just printed sheets lay against each other with pressure. The time delay between the printing nips and the set-off situations varies from a few seconds to minutes. The pressure exposed to the sheets by a folder is very short or only milliseconds. The transporting grippers press certain parts of the sheets for up to one minute. In the roped package, and also on the inserting disc, the pressure against the printed sheets can stay for hours or days. Lyne /9/ has noted, that different times have to be taken into account, when one measures ink setting and studies smearing properties of ink and paper.

2.1 Measuring of set-off

Set-off can be evaluated directly from a ready newspaper. It can be done using subjective methods, which are quite time consuming. According to SCAN standard P 36:96, a reflectometer is the primary tool for measuring set-off density, but also a densitometer can be used. With reflectometer, set-off (S) can be measured using the equation (1):

$$(1) \qquad S = \log_{10}(R_p/R_{SO})$$

where R_p is reflection of the counter paper, and R_{SO} is reflection of set-off print.

Reflectometers require a larger area for measuring which is not always possible to find from commercially printed newspapers and from a narrow set-off strip in the laboratory scale testing. Then, the densitometer is a useful tool. Many commercial densitometers are in use however, because there is no standardised device, the results measured with one densitometer are not directly comparable with the results measured by other densitometers.

If comparable results, from one commercial test printing to the other one, are wanted, then a special tool is necessary, and the same densitometer has to be used in all the tests. VTT (Technical Research Centre of Finland) has developed a special devise for this (Figure 7) /10, 11/. The device makes a set-off print on a counter paper, which is wrapped on a roll. The roll rotates with pressure along the print. Sampling and running the test takes about 20 s, which is the shortest delay time practicable.

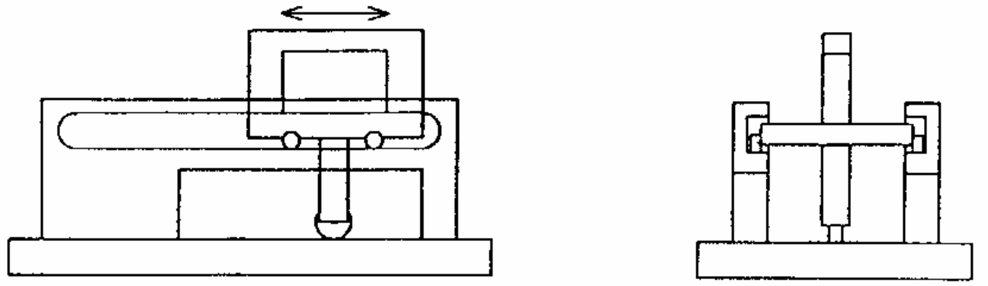

Figure 7. The schema of the set-off device developed by VTT /10, 11/.

For measuring and forecasting the set-off properties of paper and ink, a laboratory scale printing test can be done. Printing devices like IGT and Prüfbau are commonly used for the laboratory scale printing. With these presses, it is possible to vary the amount of printing ink transferred, the set-off delay time, and also the set-off pressure. The Prüfbau consists of two press units (Figure 8).

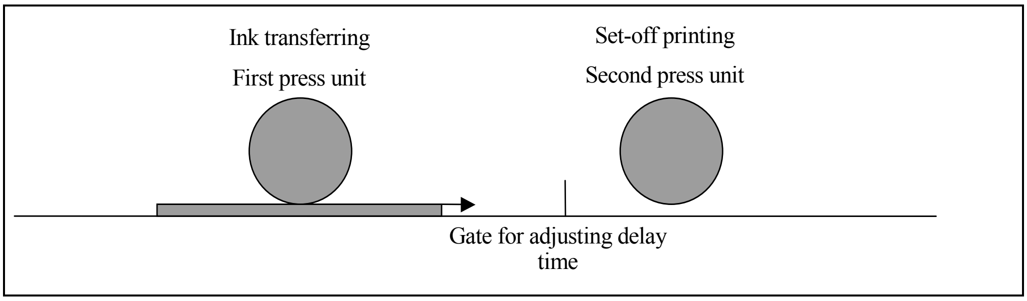

Figure 8. The schema of a Prüfbau laboratory printing press arranged for a set-off printing test.

In the first unit, ink is transferred onto a paper sample, and after an adjusted time the set-off printing is done in the second press unit. The paper sample that will be printed is fixed on a sled covered with a rubber fabric. The fabric is like an offset blanket. The printing disc for transferring ink is covered with rubber. So, the press unit for ink transfer has a soft-soft nip like the blanket-to-blanket printing unit of a production scale press. Of course, the deformation in the nip region is still different and the geometric scale is much smaller. Diameter of the disc is 63.7 mm vs. 200-400 mm of a production printing press. The comparability of the geometry of the nip conditions can be calculated by the equation (2) /12/:

(2) $1/r = 1/r_1 + 1/r_2$

where r is the combined radius (Prüfbau and $r_1 = 31.8$ mm, and $r_2 = \infty$).

The combined radius of Prüfbau is 31.8 mm. In a production press, there are two printing cylinders of approximately 200 or 400 mm on diameter. The combined radius is approximately 50 or 100 mm respectively. The geometry of the set-off situations in a printing press varied a lot and it is difficult to make a comparison with the Prüfbau set-off unit. In the set-off printing unit of the Prüfbau, a metal disc is used for imaging the hard pressing elements in folding. The counter paper is fixed on the disc with a piece of adhesive tape. Of course, the same sled with the rubber fabric is still on the other side of the paper sample.

Normal production inks can be used in Prüfbau printing but also laboratory made model inks can be tested.

Besides the different geometry, the conditions of the set-off test in the laboratory scale differ from those of production printing e.g. no dampening solution is used. However, in the laboratory scale it is possible to study the certain parameters of the set-off phenomenon by varying papers, inks, printing conditions, and set-off delay times. Also, properties measured from papers and printing inks can be correlated with set-off printing results.

3 OBJECTIVES AND THE STRUCTURE OF THE STUDY

This study focuses on uncoated newsprint grades, their surface structure, and the set-off phenomenon in coldset web offset (CSWO) printing. The surface structure optimum for CSWO printing and the set-off phenomenon itself were not very well known. The newsprint types made of different pulps, especially deinked pulp (DIP) or virgin mechanical pulps, have given the different results of set-off, but the reasons for the difference have not been clear. Finally, the question was in which way the surface structure of newsprint should be developed to produce better paper for newspaper printing. This situation was the base for setting targets for this study.

The main hypothesis of this work is that with the small amount of ink transferred onto paper in practical newspaper printing, the surface structure of newsprint dominates ink transfer, ink setting and the results of set-off, however, without forgetting properties of newsink and the printing nip i.e. the offset blanket. Less important are air permeability of paper and ink penetration into the interior of paper. The objectives of this study were:

- to have better insight into the set-off phenomenon in CSWO printing,
- to find out the main parameters in CSWO printing influencing set-off, and
- to find out the properties of uncoated newsprint type papers (made of DIP and virgin pulp), which are most important for set-off, and in which way the paper properties should be improved for reducing set-off in CSWO printing.
- The additional goal was to understand further the interaction of ink and paper in CSWO process; ink transfer and ink setting.

Among the many kinds of smearing, set-off, coming from the printing process and giving a dirty image to a printed matter, was the main objective of this study. Rub-off and smearing of the elements of a printing press are excluded from this work.

The study has been divided into three main parts: 1) literature survey, 2) theoretical discussion, and 3) experimental work.

In the literature survey, I have discussed the ink transfer onto such a rough paper like newsprint. The theories for ink transfer split the ink transfer process into the stages that makes it possible to approach these stages separately. Ink setting via absorption of the total-ink and the solvent separation were also under consideration. The careful discussions of ink transfer and ink setting allow understanding of the state of ink locating on the roughness profile of the paper surface, when a facing sheet is pressed against it in the set-off situation and set-off takes place. The relation between set-off and the properties of paper and ink was also discussed. Minor consideration was given to the importance of the fountain solution in the set-off situation.

Theoretical discussion was concentrated on creating a process analysis for set-off, in which the parameters of the set-off phenomenon are defined. The structure of newsprint was defined especially from the set-off point of view. In addition, ink setting was comprehended and calculations were made to see how much the thin and viscous ink layer could theoretically be absorbed by printing nip pressure and capillary forces.

After the literature survey and the theoretical discussion, the open questions were studied in the experimental work. So, I found the most important parameters of CSWO printing process affecting set-off. Furnish studies building different paper structures were made to see what kind of pore structure on paper is important for ink setting and set-off. Specifically I studied the differences in paper structures made of recycled and virgin fibres. The laboratory sheets and a commercial set of newsprint type papers (DIP and virgin pulp) were tested in the laboratory scale specifically regarding set-off. The DIP news was also simulated using virgin pulps and fillers. To have a basic understanding of relation between set-off and newsinks, Prüfbau laboratory printing tests with model and commercial inks were carried out. For visualising the results, a great deal of microscopic work has been included in the study.

4 LITERATURE SURVEY

In this literature survey, I have concentrated on the set-off phenomenon of the coldset offset printing using uncoated newsprint.

4.1 Introduction into set-off phenomenon

Set-off is the insufficient ink transfer from a printed paper to a pressing facing sheet. Set-off is mainly seen in the coldset web offset printing e.g. newspaper printing and also in sheet fed printing. In both cases, the ink is not dry when printed paper comes to a folder or onto a sheet pile. The ink types used in these different offset processes set during a relatively short time but ink on the printed areas of paper is not hard enough immediately after printing. In sheet fed printing, anti-set-off agents are used and sprayed onto the printed sheets to prevent set-off. These agents are not used in newspaper printing.

Because sheet fed printing has also been used in many studies of set-off, these studies are referred in the cases, which explain the set-off phenomenon as a rule. Rough newsprint, newsink and coldset web offset process are the main elements affecting set-off in the newspaper printing. The surface structure of paper has a big influence on ink transfer and ink setting. It is important also to understand the ink properties, which specifically co-operate with the surface structure of paper.

Newsprint
The common grammage range of the standard newsprint grades is 40-48.8 g/m^2. Bulk range is 1.5-1.7 cm^3/g, and Bendtsen roughness 100-200 ml/min, and PPS S20 roughness 2.5-4 µm. ISO brightness is 57-60% and opacity likely to be over 93%. In practice, the properties of commercial newsprint types can vary even more. In addition, especially the MFS grades have higher grammage and brightness values. Relatively rough pulp and weak calendering give newsprint its rough and bulky structure.

Newsink
A common formula for a coldset offset ink consists of pigments (carbon black or organic colour pigments), solvents (mineral oil or its mixture with vegetable oils), fillers, varnish and additives. The varnish in black ink can consist of natural bitumen called gilsonite and diluted into mineral oil. The gilsonite varnish is useful only in black inks because of its brownish shade. Thick oil components can also be used but they bind pigment particles together and with a paper surface only weakly so that the pigment particles can easily be rubbed away. If no drying oil is used the print can smear for a long time. CSWO printing process does not have any drying section for evaporating solvent. Instead of drying, the inks set by absorption in time. The set ink does not smear with a light touch, but it can be rubbed off by abrading. Letterpress cold set inks also have been used in testing set-off. The letterpress newsinks were formulated like those of the web offset inks but with less pigments (colorants) /7/. Offset inks also contain more resins (e.g. polyindene) than the letterpress inks in order to improve ink transfer and reduce water-logging /13/. These differences mean different rheology for those ink types.

This survey follows the order presented in Table 1, in which the main parts of the set-off process are presented and some notes important for set-off given. The keywords indicate the topics of discussion in the following chapters.

First, the CSWO printing process is studied, because the set-off phenomenon has its roots in the ink transfer in the printing nip and in the ink setting after it. In addition, the role of the offset blanket in the ink transfer is taken into account. The development of set-off itself is then discussed properly, and finally the properties of paper and ink, and also the fountain solution from the set-off point of view.

Table 1. Parts of the set-off process.

Process part	Notes	Key words
1) PRINTING NIP	ink transfer theories - contact and coverage - immobilisation - splitting	blanket conformability and compressibility, immobilisation studies, ink splitting studies, tests of theories, microscopic studies of ink location on newsprint, ink properties
2) DELAY TIME	ink setting by absorption - total-ink - mobile phase (solvent) separation	calculations, paper structure, ink properties, absorption, spreading, solvent separation
3) SET-OFF SITUATION	insufficient ink transfer - printed paper, and counter (facing) paper - contact area between ink and counter paper	paper properties - roughness - contact smoothness - compressibility
4) PAPER	properties - surface structure	roughness, contact smoothness, surface compressibility, pore structure, absorbency, nominal, and actual surface area, ink requirement
5) INK	properties - small amount transferred	ink requirement (mileage), viscosity, mobile phase %
6) FOUNTAIN SOLUTION	importance?	amount, additives, pH

4.2 Ink transfer in a printing nip

Set-off is supposed to be partly dependent on the ink transfer[1] from an offset blanket to the paper surface in a printing nip. The ink transfer controls the location of ink on the surface profile of the paper. So, the ink transfer is related to the printing nip conditions (blanket, nip pressure, and printing speed), ink properties, and the paper surface properties. /8/ That is why a target for the study of the ink transfer is to understand how the rough paper surface like newsprint performs in an offset printing nip with CSWO ink.

Generally, the ink transfer in a printing nip has been widely discussed /14/. Reviews for the item have been done by Parker 1973 /15/, Oittinen and Lindqvist 1981 /16/, Mangin et al. 1982 /17/, Lyne and Aspler 1982 /13/, and De Grace and Dalphond 1989 /18/.

For testing the ink transfer properties of papers and inks, printability testers like IGT and Prüfbau are normally used. The ink amount offered on the printing disk has been varied from almost 0 to 8-25 g/m^2 for reaching the whole range of ink amount which affects the liquid transfer /12, 19, 20, 21, 22, 23/. In practical offset printing, the ink amount used is roughly 3 g/m^2 on the rubber blanket. Oittinen and Lindqvist /16/ have given a picture drawn in about the realistic scale (Figure 9). Instead to apply Figure 10 to the whole nip situation, or also to the set-off situation with rough newsprint, and with the normal amount of ink, it gives a completely wrong idea for the ink transfer and also for the set-off situation.

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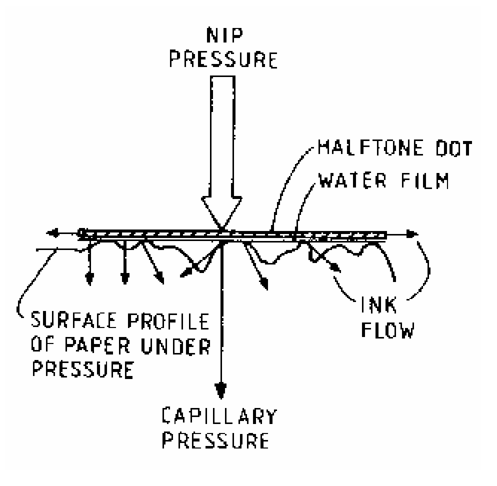
[1] Appendix 10: Särelä, S., Härkönen E., and Paulapuro H., Evaluation of Ink Transfer Theory, TAGA Annual Conference 2002 at Ashville, NC 14.-17.4.2002, TAGA Proceedings 2002, pp. 90-108. /14/



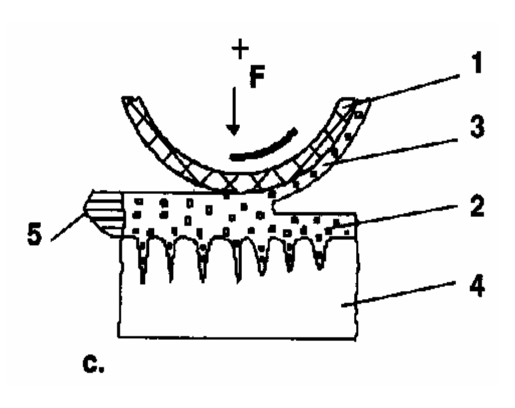


Figure 9 on the left. Formation of contact between printing ink and paper in offset newspaper printing. Figure has been drawn roughly to scale. /16/

Figure 10 on the right. A model picture given for a set-off situation. Number 1 is facing paper, 2 is ink on the paper surface, 3 is ink transferred on the counter paper, 4 is paper, and 5 is the expected concentration profile of low viscosity binding agent components or moisture of the ink. F is pressure to counter paper. /4, 24, 25/

The ink transfer is discussed often in the presentations, in which the printability properties of paper and ink have been investigated. For good print quality e.g. less dot gain, the ink transfer should be good. If x is the ink amount on the blanket, and y is the ink amount transferred to paper, good ink transfer means that the fraction of the ink transferred (y/x) from the blanket to the paper is as high as possible. This minimises the ink amount (x) needed on the printing blanket. Typical ink transfer curves printed with a GFL letterpress laboratory testing device are presented in Figure 11. The normal amount of ink on the printing plate is about 5 g/m^2 for letterpress and 3-4 g/m^2 for CSWO newspaper printing. When the ink transfer is drawn into a co-ordinate of y/x and x, the superiority of the ink transfer has been evaluated as a maximum fraction of ink transferred, which should be reached with as low an ink amount (x) as possible on the plate or on the blanket in case of CSWO /17, 22/.

For analysing the ink transfer process, the printing nip is divided into three stages /16/:

1) ink coverage of the paper surface at the inlet of the printing nip, and ink spreading
2) immobilisation (often understood as penetration) in the printing nip
3) ink splitting at the outlet of the printing nip, one part to paper and another part remaining on the plate or blanket.

Ink transfer has often been presented in the form of mathematical equations. The oldest and best-known equation for ink transfer was created by Walker and Fetsko (W-F) 1955 /20, 26/. The equation has been presented often as the following /12, 17, 19, 20, 21, 27, 28, 29, 30/:

$$(3) \qquad y = A[bB(1 - f)) + fx]$$
$$A = 1 - e^{-kx}$$
$$B = 1 - e^{-x/b}$$

where A is the 'coverage function', or the fraction of the area covered by ink; k is a 'printing smoothness' parameter (m^2/g) indicates how fast full contact is reached between the substrate and an increasing ink film x on the printing plate or the blanket (g/m^2); B is the 'immobilisation function', or the fraction of the immobilised ink; y is the ink amount on paper (g/m^2); b is the immobilisation capacity of the substrate under a given set of printing conditions (g/m^2); f is the splitting factor.

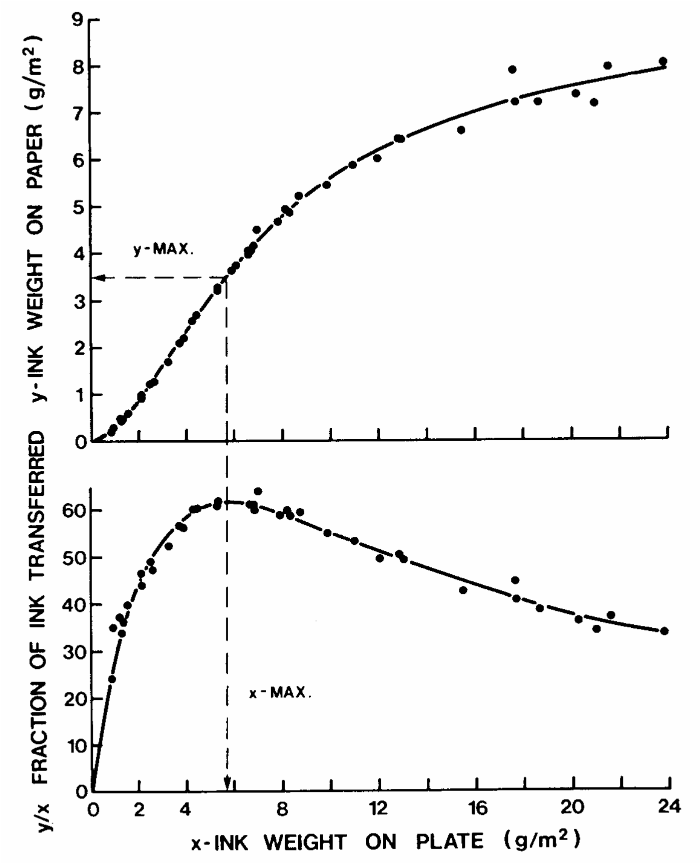


Figure 11. Typical ink transfer results printed with GFL letterpress laboratory testing device using letterpress newsink for GFL at 4.5 m/s and the nip pressure of15.4 kN/m /17/.

Walker and Fetsko /26/ also presented a simpler linear model of the equation (4) without the smoothness parameter k:

(4) $y = b+f(x-b) = b(1-f)+fx$

Zang /31/ has created a new splitting function F for explaining asymmetric ink splitting:

(5) $F = f_\infty + (f_0 - f_\infty)^{-cf_\infty x}$

where f_∞ is the splitting coefficient at high ink amounts, f_0 is the splitting coefficient of the free ink film when the amount of the ink on plate tends to zero, and c is a constant (= 2 as suggested).

4.2.1 Contact and coverage

In the W-F equation (3) the smoothness parameter k takes care of the coverage function A. This parameter might be important for applying the ink transfer theory onto a rough paper. Also, the contact area between a printing plate or blanket and paper has been an area of interest. No direct measurement, static or dynamic, from a printing press nip can be made. Some laboratory methods have been developed. The static Chapman's method is mostly used utilising total reflection of light e.g. Fogra KAM device and Pira's PPST /32, 33/. It has been presented that the contact area increases with increasing pressure, the contact points widen and the number of contact points increase /32/. The ink layer on the blanket, however, makes the situation more complex in the printing nip. Coverage increases when the ink amount offered in the printing nip increases, the slower the rougher paper is /18, 20, 26, 27/. Karttunen /28/, and Oittinen and Lindquist /16/ have mentioned that ink flows into the recesses of the paper surface during the printing nip and this can increase the contact area. Also, the offset blanket has an influence on the ink transfer.

Influence of the offset blanket on the ink coverage

Non-printed and printed areas of paper are in contact with the offset blanket in the printing nip. Besides ink, also a little, approximately 0.5 g/m^2 of the fountain solution, is transferred to paper (chapter 4.7).

The contact of the non-printed areas depends on the roughness and the compressibility of the paper surface, and especially on the compressible blanket with a rubber surface. Both, the paper and blanket have a viscoelastic nature. It means that the contact, formed in the printing nip, is depending on the nip dwell time, and the nip pressure. The coverage zone should be the whole nip exposed by nip pressure as illustrated in Figure 12, not only the inlet of the nip.

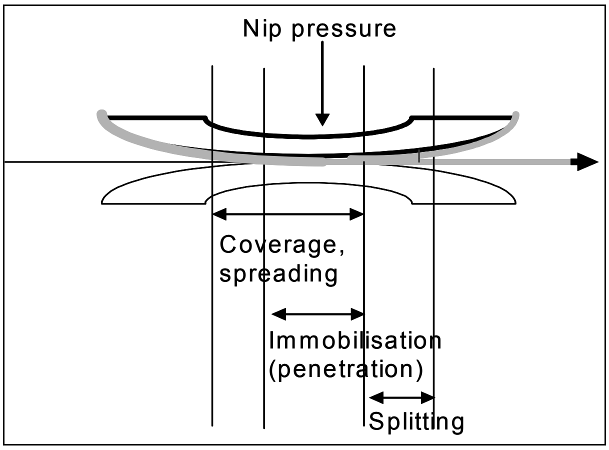


Figure 12. Ink transfer zones in a printing nip. The ink is shown with the grey line. A developed idea of the ink transfer stages for rough paper in a printing nip. The picture is not drawn to scale.

In the nip, the surface of paper contacts the ink layer on the blanket. Oittinen and Lindqvist /16/ noted that the offset blanket is the most compressive component of the nip against paper and ink. That is why it is believed that the blanket determines principally the pressure distribution in the nip when the contact is not complete. According to Lyne and Aspler /13/ and Bristow and Bergenblad /34/, the offset blanket conforms to the paper roughness helping the thin ink film transfer to paper. Bradway /35/ has noted for offset printing that a compressible printing surface (e.g. blanket) reduces the ink film thickness required to cover the sheet to a bare minimum. Upon compression, the surface of the blanket protrudes into the surface pores of paper and reduces the volume required to fill them up.

In Figure 13-15, an example of the cross section of a blanket is shown /14/. The offset blanket is flexible with its layered structure, which has one or two special compressible layers. The topmost layer of the blanket is made of relatively soft rubber. The Shore A hardness of the blanket is about 80 degrees, but the surface rubber looks softer when one thatches it with a sharp needle while observing it under a microscope.

Two simple tests were prepared to describe an offset blanket performance in a printing nip with the rough surface of newsprint /14/. In Figure 14, the blanket is pressed with a 50 µm screw driver and in Figure 15, the tool is a 1 mm screw driver. It can be seen how the rubber surface has conformed by the pressure of the narrower tool without damaging the surface. Instead, the wider tool (Figure 15) has compressed the whole blanket but the rubber surface layer has not changed at all.

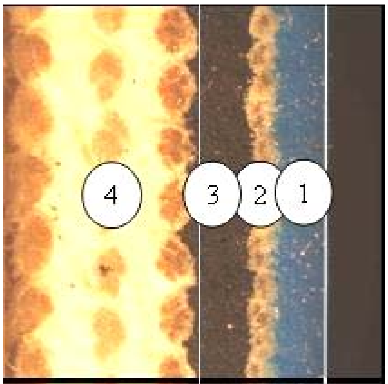


Figure 13. Example of a cross section of an offset blanket. Thickness of the whole blanket is 1.95 mm. /14/

1. *Rubber surface*
2. *Stabilizing fabric ply*
3. *Compressible layer*
4. *Base fabric ply*

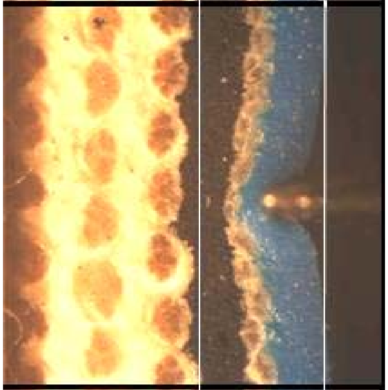


Figure 14. Cross section of a compressible blanket, with localised deformation arising from a 50 µm wide screw driver. The rubber layer is not damaged. /14/

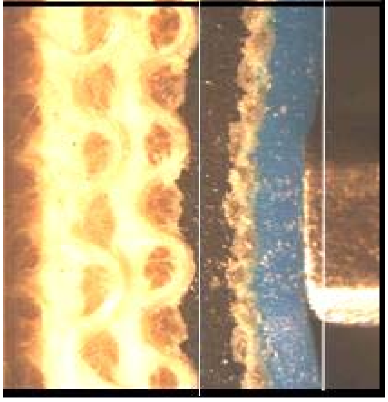


Figure 15. Cross section of a compressible blanket, as deformed by 1 mm wide screw driver. /14/

The conclusion of these tests is that the offset blanket has two functions for giving better ink transfer to the rough paper surface. More or less the rubber surface can conform to the roughness profile of the paper surface in the scale of approximately some tens of microns maybe up to 0.5 mm. The compressibility of the blanket compensates for thickness variations of paper in the formation scale up to 10-15 mm. This makes it possible to reach quite reasonable print quality with the rough paper grades in printing newspapers.

Parker /15/ has adopted the idea of the conformability to the PPS roughness measuring device applying a soft backing under the paper sample (Figure 16). The soft backing conforms to the thickness variations of paper. The picture also describes how the ink film on the hard letterpress plate has contact with the paper surface by aid of the soft backing.

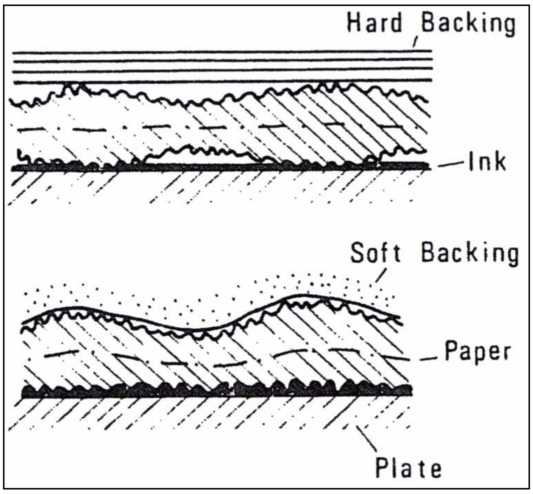


Figure 16. The flexing of printing paper induced by a soft backing /15/.

According to the information collected from the www home pages of blanket producers the roughness values of the blankets vary considerably between 2-12 µm whereas Ifra /36/ has proposed a value for newspaper printing of 1 µm. The differences of the figures may be symptomatic of the measuring method. However, the rough surface is able to accommodate a higher share of ink compared with a smoother surface.

<ins>Roughness volume of paper vs. ink coverage</ins>

The coverage of ink depends on the completeness of the contact area between the ink layer on the blanket and the paper surface. The coverage is important for reaching the target print density. However, the thin ink layer, roughly 3µm on the blanket, can not fill the whole roughness volume, and all the voids and cavities (15-20 µm deep) on the rough surface of newsprint. This conclusion can be made e.g. from the drawing in Figure 9. The roughness volume of paper can be measured with a Bristow wheel type method /37, 38, 39/.

Salminen /37/ tested water sorption into different papers with different roughness using the method basically similar to the Bristow wheel. The sorption results extrapolated to ‘zero time’ are presented in Figure 17 as the function of PPS 20 roughness. It appears the roughness measured with PPS 20 in µm would represent the roughness volume in ml/m^2 of water under the given pressure. Because the specific weight of newsinks is roughly the same as water, we could transfer the results to the ink coverage. However, the relatively high variations of the results in Figure 17 have to be noticed. Differences in the compressibility of papers tested could be one explanation for the variation. The mechanical pressure exerted on the paper clearly decreased the liquid volume transferred to paper also as extrapolating the results to zero contact time.

Salminen /37/ also noted that the zero time is not real, and the appearance of the liquid sorption curve between zero, and the experimentally measurable contact time (0-2.5 ms) is unknown. The sorption figures include the absorption during that time, too. It takes less than 1 ms to fill

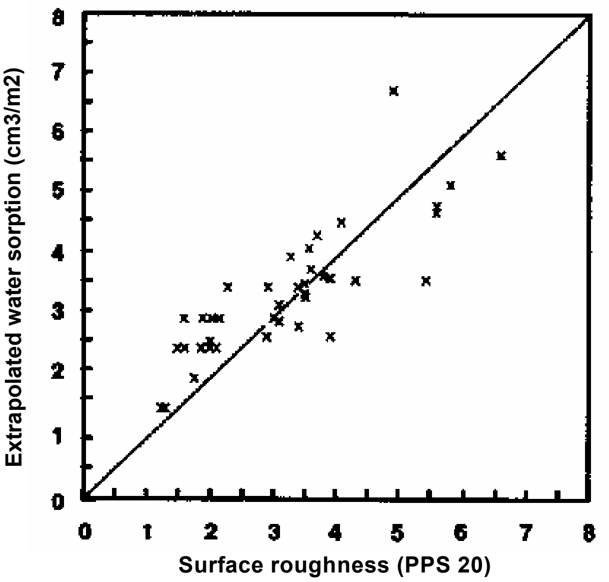


Figure 17. Relationship between PPS 20 roughness values and to the zero contact time extrapolated water sorption volumes of different papers (roughness volume under the given pressure). /37/

the roughness volume with water. He considered possible, that the filling of the roughness volume with a liquid depends on: external pressure, spreading and capillary pressures, pressure drop due to liquid flow, and counter pressure of air; also the absorption into the pores of paper starts immediately after contact between water and the paper surface. This list may also be valid for comprehending the ink coverage.

Influence of the surface tension on ink coverage

The coverage is not influenced as much by the interfacial tension of the inks against paper, because it is small (~30 mN/m) in comparison with the nip pressure (~20 kN/m). So, it was supposed to be neglected in calculation of the degree of the contact between ink, and a paper surface. /16/ Also, De Grace and Mangin /22/ have found, that the surface free energy is not important in the ink transfer, as the curve of the fraction of ink transferred vs. ink on the plate was the same for a polytetrafluoroethylene (Teflon) film and for a polyester film in spite of their different free surface energy, 18.5 and 43 mN/m respectively. The ink transfer to the surface of the Teflon film had been a surprise, because the surface tension of the ink was much higher i.e. 30 mN/m vs. 18.5 for the Teflon film. However, afterwards ink crawled forming droplets. It was counted as being possible, according to Eriksson /40/ that the surface tension of a liquid falls dramatically under pressure. Another reason for the ink transfer to the surface with the low energy could be the force caused by the nip pressure being superior to the surface forces.

Influence of entrapped air

The ink layer can entrap air between the ink layer on the blanket and the paper surface, while the paper web runs into the inlet of the printing nip. This has been seen by studying the asymmetry of splitting. /22, 23/ Also the counter pressure of air in the surface voids of paper can decrease the contact between ink and paper /28/. Air permeability of paper decreases the influence of air on the contact.

Printing speed

A higher printing speed means a shorter dwell time in the printing nip. Paper and the rubber blanket have less time to compress and conform and ink can flow less. Larsson and Sunneberg

/41, 42/ investigated paper/ink interaction with newsprint paper grades printing them with a GFL laboratory letterpress printing machine and with simple low viscosity ink prepared in a laboratory (15% pigment and 85% mineral oil of 0.454 Pas viscosity). The pigment was marked with radioactive iodine. They found that increasing printing speed from 1 m/s to 5 m/s, the ink pigment penetration decreased from 21 µm to 18 µm. Also, the ink pigment amount on the topmost surface of the paper increased with the increasing printing speed. The ink on the topmost surface was taped off after 24 h with an adhesive tape and the pigment was measured detecting the radioactive iodine. The pigment penetration was measured using the method published by Fifi and Arendt /43/. This method is based on Kubelka-Munk's theory and it does not differentiate if the ink penetrated locates in the capillaries or only deeper on the roughness profile of paper. Obviously, the results were greatly influenced by the relatively low viscosity of ink.

Printing nip pressure vs. ink coverage

Singh et al. /27/ measured the ink coverage with an image analyser when smaller amounts of ink were transferred onto newsprint. The increasing nip pressure improved the ink coverage with the small amount of ink offered on the printing form. Printing conditions were metal disk, rubber blanket as backing, IGT offset black ink, speed 1 m/s, and nip pressure variable. An example of the results can be seen in Figure 18. Covering rate was found to be much faster with super calendered papers than that with newsprint types.

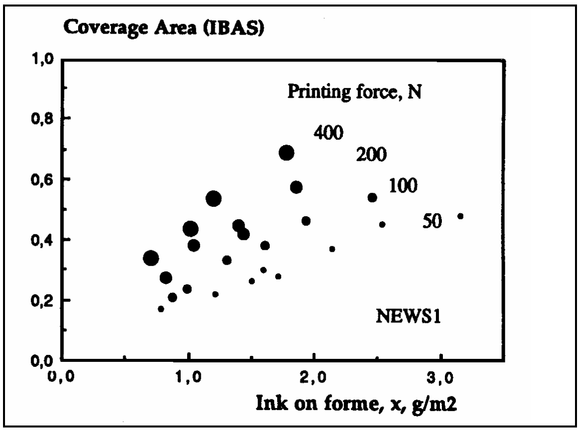


Figure 18. Relationship between the coverage area on newsprint at different printing pressures of IGT printability tester determined by image analysis (IBAS), and the amount of ink on the printing disk. /27/

Effect of the lateral ink flow under pressure on the ink coverage

During the nip time, not only the compressibility and conformability of paper and blanket, but also the lateral ink flow increases the contact, and the ink coverage of paper. It has been thought /13, 16, 23, 28/, and also it has been seen /44, 45, 46/ that ink flows sideways from the contact points to the surface cavities with the aid of the nip pressure. For evaluating the ink spreading, it is suggested to use the equation (6) which is for a liquid spreading between two plates, and also for microscopic surfaces. /16, 47/

$$\frac{dr}{dt} = \frac{\Delta p H^2}{3r\eta} \tag{6}$$

where r is radius of the round liquid layer, Δp is pressure difference between the plates, H is thickness of the liquid layer, and η is viscosity of the liquid.

Bohan et al. /48/ has made theoretical calculations of an ink dot gain and absorption. The calculation was made with the values of the parameters which are mainly comparable to the sheet fed printing conditions and inks. One example of the calculations was the spreading of a printed dot of the initial diameter of 121 µm during the period exposed by pressure of 2 MPa. It was noteworthy to find from this calculation how quickly the thickness of ink layer in the dot decreased from 7 to 4 µm. It took only 0.4 ms with the ink viscosity of 7 Pas, which is comparable to the viscosity range of CSWO inks, and to the thickness of the ink layer in the plate-blanket nip of a printing machine.

Based on e.g. the Bohan's et al. /48/ calculation in the case of microscopic surfaces (fibres) of a rough paper, it is obvious that also the thickness of the ink layer (*H*) decreases remarkably via the ink flow into the surface voids. This changes the flow conditions in the gap between the fibre and the blanket. In addition, CSWO inks are viscoelastic and shear thinning /49/. So, these things make it complex to use the equation (6) for calculating the lateral ink flow.

The calculation in ref. /14/ has been made for ink flow between a fibre and a hard plate located parallel with each other. Developed equation (7) gives an approximation of how high local pressure is needed for squeezing ink away during the given dwell time. The development of the equation (7) is presented in Appendix 10.

$$(7) \qquad h_2 = \sqrt{\frac{1}{\frac{P_{av} \cdot \Delta t}{2\mu L^2} + \frac{1}{h_1^2}}}$$

Using the numerical values below the results of the equation (7) are illustrated in Figure 19.

P_{av} is the average pressure in the ink layer. and h_2 is the thickness of ink layer after Δt = 1 ms.
The width (2L) of the contact surface between fibre and printing plate may vary from 10 to 40 µm.
Length (b) of the contact area is 0.5 mm (not needed in the final calculation).
The thickness (h_1) of the ink layer at the beginning of the inspection period is 3 µm. The dwell time (Δt) in printing nip is app. 1 ms.
As first estimate for the fibre velocity towards the printing plate, it is assumed that the thickness of the ink layer approaches 0 in 1 ms. This gives the velocity in z direction 0.003 m/s.
The viscosity (µ) of the ink is 10 Pas.

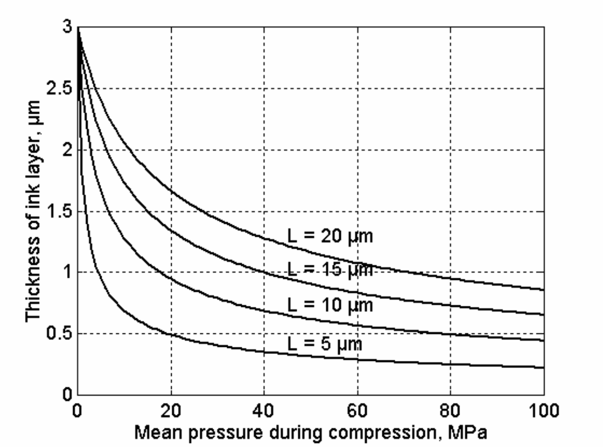


Figure 19. The thickness of ink layer as a function of mean pressure during the compression. The change happens in 1 ms; the half of the fibre width L of the contact area is as curve parameter. /14/

A fibre surface is often about 20 µm wide because of the round shape. In the solid printing area, the topmost fibres are often clear of ink. Figure 19 illustrates that the pressure squeezing almost all the ink away is as high as approximately 50 MPa. The fibres collapse in the paper making process but those not calendered flat have a groove in the middle of the surface. The depth of the groove is about 2-3 µm and ink stays in the groove but the edges of the groove are also cleared of ink by the high local pressure. /14/

The parameters of the Walker-Fetsko equation (3) attempt to describe the ink transfer only with the properties of paper: roughness and absorption. Oittinen /12/ found that the ink transfer at the low amounts offered on the plate is controlled by the coverage. She investigated the influence of the ink properties on the ink transfer also in the case of very rough paper. The inks, which were markedly structured at low shear rates, gave poor ink transfer in printing. Shear thinning and viscoelasticity of ink improved the ink transfer and the coverage on paper while the high tack and the shortness of ink decreased it.

Conclusions for the ink coverage: The ink amount offered in a printing nip influences the ink coverage of rough paper grades. It is also seen that the coverage of the rough newsprint surface, especially with the relatively thin ink layer on the offset blanket, depends on at least:
nip pressure, nip time (printing speed and the nip geometry), lateral ink flow, ink rheology (viscosity, shear thinning, viscoelasticity, tack, shortness), and in addition conformability, compressibility, and viscoelasticity of the blanket and the paper surface. There can also be a drop of the hydraulic pressure via the lateral ink flow, and the counter pressure of air can decrease the ink contact with paper. In the newsprint grades, the type of roughness includes deep and steep voids and cavities, shallower or deeper recesses, and flat, round, or grooved (dented) surfaces of fibres. Some areas receive more calendering whilst others less, depending on the local grammage variation (formation) that causes roughness variation. All these factors control the statistical probability for the thin ink film to cover the rough paper surface.

4.2.2 Immobilisation, penetration

It has been suggested that the immobilisation of ink takes place in a printing nip via ink penetration /12, 13, 16, 20, 22, 27, 49/. Parker /15/ noted that ink immobilises in or on the paper surface and he also stressed the differences of the ink transfer in the thin and thick ink film regime. Nordstöm and Grön /29/ noted that immobilisation parameter b, in fact, is related to substrate properties like roughness and absorbency, i.e. surface area and the roughness volume available.

Sunnerberg /42, 50/ has discussed the connection between the pore structure of the paper surface and ink penetration. He divided the voids of the paper surface into recesses and pores, and noted that it is useful to distinguish the ink penetration into the recesses, because in both cases the controlling mechanisms are different. The recesses can be defined as cavities that do not offer any noticeable resistance to the ink penetration.

In a printing nip, the total-ink (without solvent separation) should be penetrated, not only e.g. the solvent or the mobile part of the ink suspension. Although the mechanism of the solvent separation is not well known, the nip time, one to a few milliseconds seems to be too short for that phenomenon. Many conclusions of the immobilisation have been made from the results of coated paper grades and sheet fed printing inks, but the idea has also been applied to the results of newspaper printing, letterpress or CSWO /16, 22, 27/.

Lucas-Washburn's equation (8) is the sum of the flow speeds of a liquid in a capillary caused by capillary pressure and an external pressure /37, 51/.

(8) $$\frac{dl}{dt} = \frac{r\gamma \cos\varphi}{4\eta l} + \frac{pr^2}{8l\eta}$$

where l is length of the tube, γ is the surface tension of the liquid, $\cos\varphi$ is the contact angle between the liquid and the wall of the capillary, r is the radius of the capillary, p is the difference in pressure at the ends of the tube, and η is the viscosity of the liquid.

The start can be created from the last part of the equation (8) applying capillary pressure $p = 2\ \gamma\ \cos\varphi/r$ instead of the external pressure. The last part of the equation (8) comes from Poiseuille’s law of viscosity (equation 9). Transformation for the equation (8) has been made by changing the volume rate to the longitudinal rate in a cylindrical tube.

(9) $$v = \frac{\pi p r^4}{8l\eta}$$

where v is flow volume speed through the tube, other symbols are as in the equation (8).

According the results of e.g. in ref. /38, 51/, absorption of oils into the porous structure of paper agrees Lucas-Washburn equation when the external pressure is zero and there is no lack of liquid.

Also Kozeny’s integrated equation (10) is used for explaining the ink and varnish penetration /16, 52, 53/.

(10) $$h = m\sqrt{\frac{2pt}{k_0\eta}}$$

where h is the depth of penetration, m is the main hydraulic radius, and k_0 is a constant. The pressure p is the total pressure including the externally applied pressure, as well as the capillary and the hydrostatic pressure.

In Kozeny’s equation, the main hydraulic radius and a constant is used instead of the capillary radius of Poiseuille’s law. The main hydraulic radius can be calculated if the penetration depth is measured independently. According to Hsu /52/, the compression of paper caused by such a high pressure like a printing nip pressure decreases the liquid penetration clearly.

Because the capillary pressure is very small compared to the nip pressure, the first part of the Lucas-Washburn equation (8) can be neglected in the case of the penetration in the printing nip, and also the influence of the capillary pressure in Kozeny’s equation (10). Thus, Poiseuille’s law of viscosity has been used to explain the absorption volume rate of ink into paper pores in a printing nip /9, 16/. When one uses Poiseuille’s law, it has to be assumed that an external pressure such as printing nip pressure should push liquid through the capillaries. The counter pressure of air is not taken into account. The penetration volume through a capillary is a function to the fourth power of the pore radius. Thus, the pore size distribution should have a great influence on the liquid penetration into the pore structure. Oittinen and Lindqvist /16/ have made estimations for absorption depth using the absorption speed of 0.02 m/s in a capillary with a radius 2 µm, ink viscosity of 10 Pas, and with nip pressure of 4 MPa. During the time exposed by the nip pressure, the absorption into the capillary could be approximately 10 µm. The figures chosen for the calculation are not far from the practical CSWO printing, but the calculation demands that there is enough ink for penetration. This demand commands the lateral ink flow towards the capillary from approximately 3 µm thick ink layer in the printing nip. The calculation above has been applied on newspaper printing by reviewing that ‘during the time of the contact in the nip, the ink can penetrate into paper to the extent of approximately 10 µm’ /7/.

Coupe and Hsu /53, 54/ penetrated inks and varnishes into a super calendered (SC, apparent density 1090 kg/m^3), and a rough book paper (Bendtsen porosity 45 and about 2200 ml/min, and roughness 45 and 700 ml/min respectively). The penetration was measured as a drop in reflectance of the light reflected through the backside of the penetrated paper (like print through). In the case of SC paper, the amount of ink or varnish, which was able to flow into paper under a given pressure during the definite time and with the definite viscosity, was limited. This was regardless of how much liquid was available. In the case of the very porous and rough book paper, there was no such limit, but the liquids penetrated even up to 26 g/m^2 transferred to paper.

Chou and Tasker /21/ studied the ink transfer and the mileage of model heatset ink formulas. They tested the ink transfer with the (W-F) equation (3). On coated grades, they found that well dispersed inks had an ink immobilisation lower than the more flocculated ones. They concluded that the bulky pigment flocks may not block the pores of the substrate as effectively as the small, well-dispersed pigments. The authors noted also that the ink pigment flocculation can release excess solvent, which can absorb into the substrate surface. The conclusion of the ink transfer curves was that the contribution of the immobilised ink to the transferred ink was insignificant on the smooth, coated grade with fine pores.

Grace and Dalphond /18/ evaluated the pigment penetration by measuring print through after extracting the solvent of the GFL letterpress newsink with petroleum, using the method of Larsson and Trollsås /55/. The print through of the calendered and uncalendered newsprint remained the same when the solvent was extracted 3 s or 72 h after printing. Thus, there was no ink pigment penetration during that period. All the pigment penetration had to take place in the printing nip and in 3 s after printing. The solvent absorption caused the changes in print through after that. The pigment penetration during the shorter periods than 3 s were not reported.

Testing the immobilisation parameter of W-F equation (3), results have been attained which have caused criticism of the theory of Walker and Fetsko. With a large range of the ink amount up to 20 g/m^2, when all possible immobilisation has taken place, the immobilisation parameter b has been found to be possible to compensate with the splitting coefficient f, when the paper types and printing conditions were varied, but the ink used was constant /17/. The parameter b could be compensated with the smoothness parameter k, when the only variable was ink rheology and the printing was done on the smooth coated grade /21/. In the case /12/ of high viscosity range (5-60 Pas) of 'inks', e.g. non-Newtonian vehicles printed onto the rough uncoated sheet, the differences in vehicles in immobilisation could be explained by the large differences in viscosity. Calculating from these results, no good cross-correlation could be seen between the parameters of the W-F equation.

Kent and Lyne /56/ used the master creep equation proposed by Colley and Peel /57/. The thickness of newsprint exposed to a nip pressure of 2.5 MPa during 1 ms dwell time reduced theoretically about 25% and the void volume of the paper decreased about 50%. This closing of paper should be expected to reduce drastically the amount of ink impressed into paper, over that which would be impressed, if the structure remained uncompressed. Hsu /16, 52/ has also observed from a theoretical calculation that penetration decreases with the increasing compressibility of a paper surface. However, Coupe and Hsu /53/ have concluded that although the paper compresses greatly, the vertical pores are not as much affected by the pressure. Only the fibres are more closely packed under the applied pressure, and the penetration would be expected to take place in the vertical pores.

Conclusions of the ink immobilisation:

Immobilised ink has been defined as the part of the ink transferred, which does not participate in splitting. Mostly the comprehending of the immobilisation of ink during the printing nip dwell time seems to follow the idea presented earlier in Figure 10: The whole roughness volume is filled by ink and the hydraulic pressure in the printing nip causes penetration of the ink; immobilisation is equal to the penetration. However, immobilisation is less important with smooth coated paper grades, and also when only the small ink amounts such as in the CSWO printing is transferred to rough paper. It is also noted that the compression of paper in a printing nip can make the uncoated paper surface more closed for the ink penetration. The lower viscosity inks are more sensitive to penetration. Also, higher ink amounts, higher pressure, and slower speed can increase penetration.

With small ink amounts, the larger gaps and voids of the paper surface and the topmost fibres divide the continuous ink layer on the blanket into smaller areas. Thus, the hydraulic pressure in the ink layer can not be created by nip pressure continuously over the whole nip. This conclusion can be made from the incomplete ink coverage and therefore the discontinuous ink layer transferred onto the rough surface of newsprint.

4.2.3 Splitting

In the ink film splitting after a printing nip, first the cavitation takes place, then begins filament formation, and finally the rupture of the filaments.

Theoretically, based on symmetry, a liquid film splits 50/50 to the both surfaces of the opening nip. In practise, if the ink amount offered is small, the fractional ink amount transferred to paper (percents of the offered ink amount) is below 50% and the coverage is not complete, but it is supposed that it increases to a maximum, when the coverage reach 100%. If the ink amount for transferring is still increased, the fractional ink amount transferred to paper decreases, and finally levels off to the level typical for the paper and ink tested (see Figure 11). Commonly, with smooth coated papers, the maximum stays below 50% and with rough uncoated grades like newsprint, the maximum rises above 50%. In the case of newsprint, the higher fraction staying on the paper in the splitting is explained mainly due to ink immobilisation i.e. the ink penetration /22/, because the immobilised part of ink does not split. Less consideration has been given to the lower results of the maximum fractional ink amount for the coated grades. However, Oittinen /12/ remarked that the immobilisation is less important with coated grades than with rough uncoated ones. Also, Chou and Tasker /21/ and Aspler et al. /58/ agreed that with their results.

According to Oittinen /12/, after the nip, when the ink layer splits, the properties of the ink are decisive i.e. tack, shortness and viscoelasticity. However, according to Aspler et al. /58/ in the case of newsprint with the small ink amounts transferred onto the paper, there is not enough ink in the printing nip to fully cover the paper, much less saturate the surface pores. Therefore, there is little or no free ink film, and in the splitting, the cavitation occurs near the nip centre. Also, they found that in this case different inks performed in the same way in splitting. It can be supposed that the roughness and the thickness of the ink film are also important factors in splitting.

Asymmetry in splitting

Air entrapped between the ink layer and the printing substrate decreases the ink transfer. It was seen in the study of De Grace et al. (1987) /23/. They found that ink splitting is asymmetric because not only the rough surface of a substrate but also the air entrapped under the ink layer. It was noticed, when ink transferred onto a smooth, non-absorbing metal plate it was also split asymmetrically in the plate-to-plate nip. The higher the speed and the thickness of the ink layer the lower was the fractional ink transfer. The air was removed from the space between the ink film and the recipient plate by repeating the printing procedure up to 32 times, when the fractional ink transferred was reached close to 50% (Figure 20).

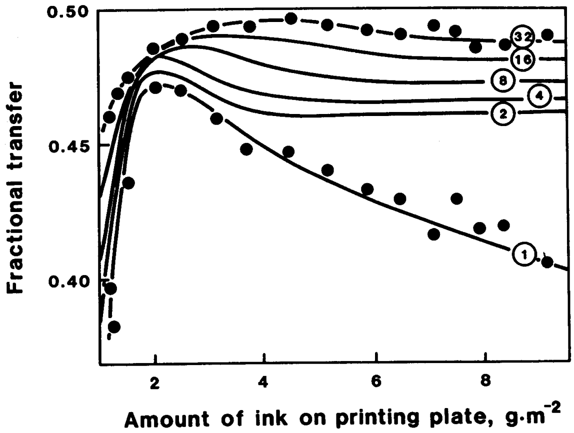


Figure 20. Fractional ink transfer in the plate-to-plate nip for different number of impressions. After 32 impressions, splitting is coming close to symmetric. /23/

Filament formation

De Grace et al. (1991) /59/ studied the ink splitting also by photographing the nip exit of the IGT model AIC2 laboratory printing device. They used model inks with different viscosities, and observed the filament formation with a high speed camera. The printing substrate was a roughed polyester film to prevent immobilising of ink via penetration. The static nip width was 4.6 mm, speeds were 1, 3, and 5 m/s, and nip dwell times 4.6, 1.5, and 0.9 ms respectively. According to the calculation, acceleration of filaments at the speed of 2.6 m/s is more than 30 times higher than the gravitational acceleration (*g*), comparable to production printing at 7.9 m/s. The filament length at rupture was less than $^1/_2$ mm at less than 4 mm from the nip centre with 3.5 g/m^2 being the ink on the printing disk. It can also be seen from the results in Figure 21 and 22 that with such a thin ink layer of 3.5-4 g/m^2 for splitting, the filament length was not clearly dependent on the ink low shear viscosity (100 1/s) of 1.7-10 Pas. It was dependent only very slightly on the printing speed of 1-5 m/s (acceleration of filaments (γ_f) of 43-1063 m/s^2 respectively). The trend decreased with increasing speed.

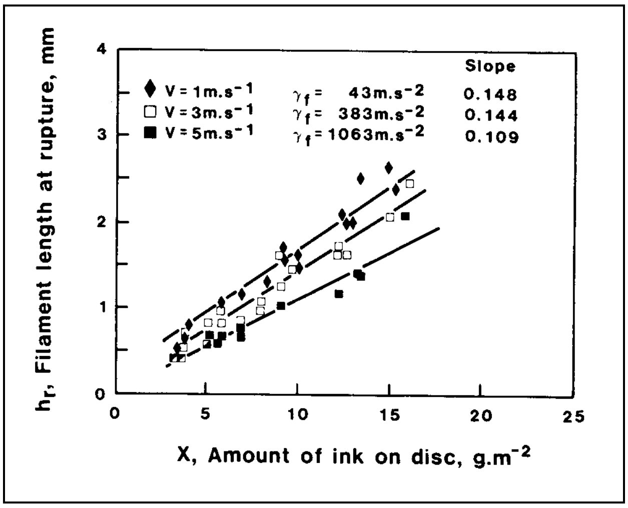
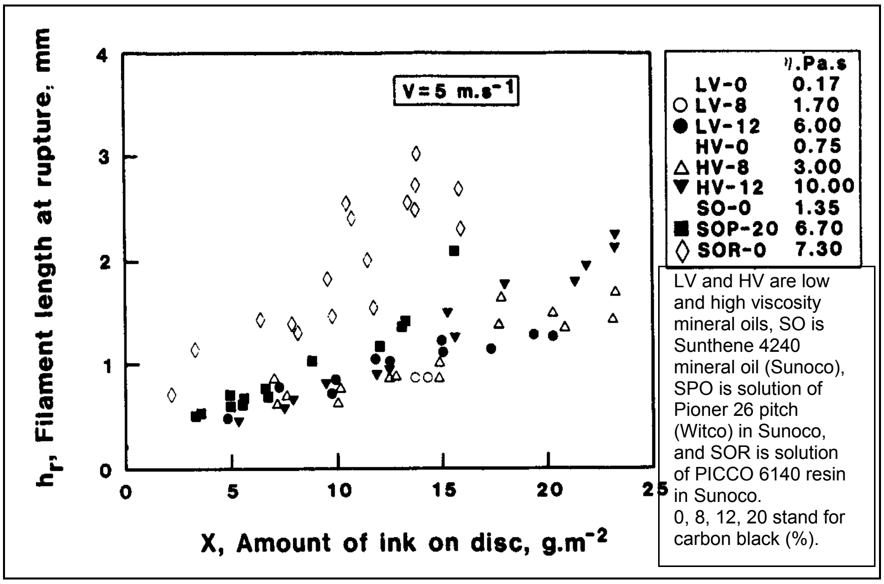


Figure 21. Filament length at rupture on the IGT AIC2 printability tester with different printing speed (v), shear viscosity (100 1/s) of the ink (SOP-20) was 6.7 Pas. γ_f is acceleration of filaments /59/.



LV and HV are low and high viscosity mineral oils, SO is Sunthene 4240 mineral oil (Sunoco), SPO is solution of Pioner 26 pitch (Witco) in Sunoco, and SOR is solution of PICCO 6140 resin in Sunoco.
0, 8, 12, 20 stand for carbon black (%).

Figure 22. Filament length at rupture on the IGT AIC2 printability tester with different ink viscosity (100 1/s), and a constant printing speed of 5 m/s /59/.

Although the filament formation does not seem to be of high importance in the practical ink transfer of the CSWO printing, ink misting should not be forgotten, which has been found to be dependent on e.g. filament length, viscosity, and speed /12/.

Back transfer of ink in the splitting

Oittinen /12/ has investigated the back transfer of ink in the splitting adding a parameter into the Walker-Fetsko equation. She noted that the immobilised ink penetrated into larger pores could be activated during splitting. The more structured inks, like the sheet fed inks, are likely to be susceptible to back transfer by splitting also in wet-on-wet multicolour printing. Analogous to this, the less structured inks, like newsinks, are not as susceptible to back transfer.

Elastic resilience of compression after printing nip

In the arrangement of Coupe and Hsu /53/, the pressure against an SC paper fell down to the minimum in the order of 0.01 s, and in the oscilloscope image one could see that the compression of paper (measured as the change in light reflectance) reverts during the same time. According to that result, it can be supposed that the paper compression caused by the printing nip pressure reverts e.g. between printing units, but the time period needed for reverting the compression could be longer than the nip time of about 1 ms. Oittinen and Lindqvist /16/ remembered, reverting of the compression at the outlet of the nip can cause suction for ink into the opening pore structure. However, they had not found it as a measurable magnitude.

4.2.4 Survey of the ink transfer theories

Besides the Walker-Fetsko equation (3) a range of equations have been created for describing ink transfer. Mangin et al. /17/ has made a survey of the ink transfer theories. The equations presented in the survey are listed in Table 2.

In the equations, the main focus has been the coverage and the immobilisation factors. Mangin et al. evaluated the equations by mathematical modelling with 29 letterpress laboratory printing tests. They varied the nip pressure and the printing speed with five newsprint types but with only one letterpress ink. They found e.g. that changing the end point of the ink amount from 25 g/m^2 to 12,5 g/m^2 on the plate, the five newsprint samples had different characters to the ink transfer (still 12,5 g/m^2 is too high for newspaper printing). Also, the parameters (k, b, f, A_0) of the equations had either too high a main standard error or a cross-correlation among the parameter estimates.

Singh et al. /27/ compared the mathematical coverage functions and found Hsu's /60, 61/ coverage equation (11) superior to Walker-Fetsko's coverage function A and also to that of Karttunen's /28/ modification A_0 (Table 2).

(11) $A/(1-A) = kx^n$; $A<1$

where A is the ink coverage area and k and n are constants, k is related to the smoothness of paper and x is ink amount on the printing plate or blanket.

The coefficient of determination r^2 for Hsu's equation (11) had been found to be greater than 0.97 in most cases; n and k did not cross-correlate.

With the equations in table 2, the ink transfer of the very large range of ink amounts on offer, 0-25 g/m^2 has been explained. However, in different film transfer processes, the liquid film thickness varied a lot. In CSWO printing, the practical ink amount offered is approximately 3 g/m^2 for solid tone of one colour printing, and maybe 5-6 g/m^2 for heavy four colour printing (tonal coverage 280%). In coating of paper with a metering size press, the coating colour applied to paper can be up to 15 g/m^2. Nordström et al. /29, 62/ have divided the film transfer curve into three regions (Figure 23). In Region I, the ink transfer increases with increasing film thickness but the filling in the pores, and the coverage of all surfaces are incomplete. Thus, Region I is interesting in characterising the structures in the involved surfaces. All the involved surfaces are supposed to be fully covered when the percentage transfer is a maximum at the end of Region I. In Region II, the film immobilisation and the absorptive and volumetric properties of the substrate determine the transfer and with increasing film thickness, the influence of the substrate diminishes. In Region III, the characteristic feature is an even split of the free film. The percentage film transfer remains constant. Chagas and Baudin /20/ also have presented a similar idea.

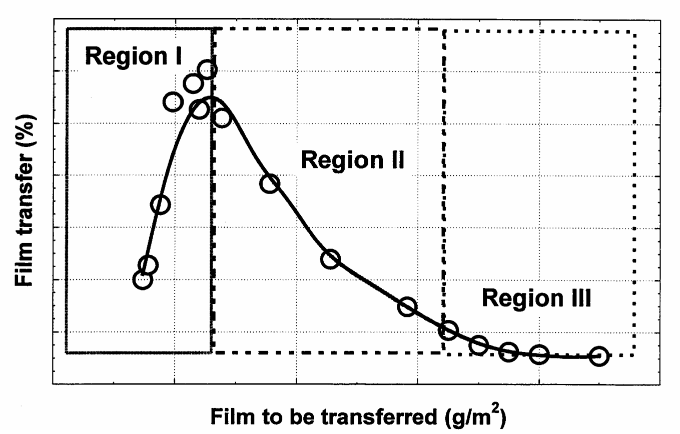
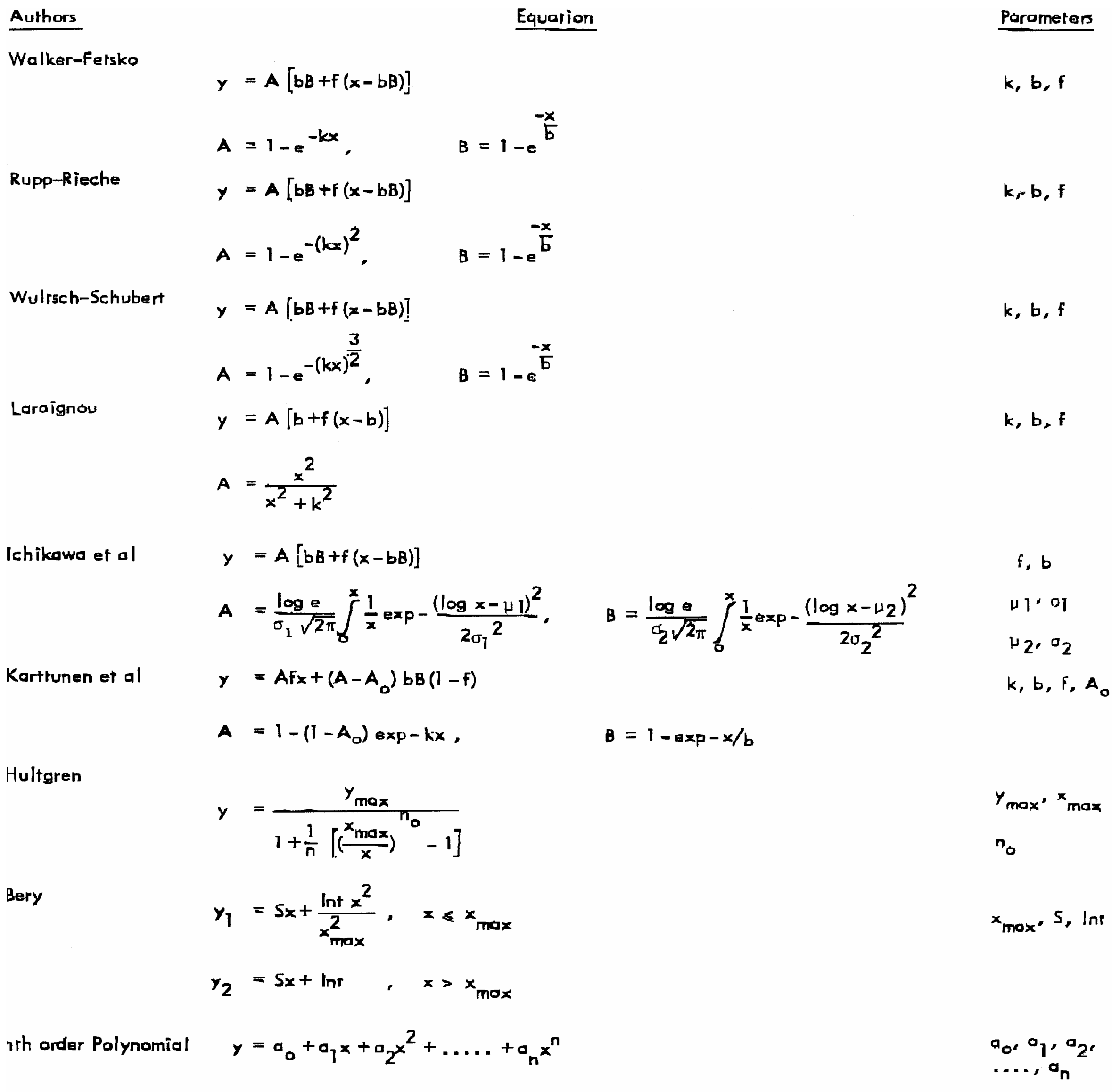


Figure 23. Percentage film transfer vs. ink film on a ink transfer roll from showing the regions I, II, and III /29/.

Table 2. Ink transfer equations for a solid print /17/.



Authors	Equation	Parameters
Walker-Fetsko	$y = A\left[bB + f(x - bB)\right]$ $A = 1 - e^{-kx}, \quad B = 1 - e^{\frac{-x}{b}}$	k, b, f
Rupp-Rieche	$y = A\left[bB + f(x - bB)\right]$ $A = 1 - e^{-(kx)^2}, \quad B = 1 - e^{\frac{-x}{b}}$	k, b, f
Wultsch-Schubert	$y = A\left[bB + f(x - bB)\right]$ $A = 1 - e^{-(kx)^{\frac{3}{2}}}, \quad B = 1 - e^{\frac{-x}{b}}$	k, b, f
Laraignou	$y = A\left[b + f(x - b)\right]$ $A = \frac{x^2}{x^2 + k^2}$	k, b, f
Ichikawa et al	$y = A\left[bB + f(x - bB)\right]$ $A = \frac{\log e}{\sigma_1 \sqrt{2\pi}} \int_0^x \frac{1}{x} \exp - \frac{(\log x - \mu 1)^2}{2\sigma_1{}^2}, \quad B = \frac{\log e}{\sigma_2 \sqrt{2\pi}} \int_0^x \frac{1}{x} \exp - \frac{(\log x - \mu_2)^2}{2\sigma_2{}^2}$	f, b μ_1, σ_1 μ_2, σ_2
Karttunen et al	$y = Afx + (A - A_o)\, bB(1 - f)$ $A = 1 - (1 - A_o) \exp - kx, \quad B = 1 - \exp - x/b$	k, b, f, A_o
Hultgren	$y = \frac{y_{max}}{1 + \frac{1}{n}\left[\left(\frac{x_{max}}{x}\right)^{n_o} - 1\right]}$	y_{max}, x_{max} n_o
Bery	$y_1 = Sx + \frac{Int\, x^2}{x_{max}^2}, \quad x \leqslant x_{max}$ $y_2 = Sx + Int, \quad x > x_{max}$	x_{max}, S, Int
nth order Polynomial	$y = a_o + a_1 x + a_2 x^2 + \ldots\ldots + a_n x^n$	$a_o, a_1, a_2, \ldots, a_n$

Nomenclature of the equations

x = ink weight on plate (g/m² or µm)
y = ink weight on sample (g/m² or µm)
Y = y/x = fractional ink transfer
x_{max} = x coordinate of the peak in the fractional ink transfer curve
y_{max} = y coordinate of the peak in the fractional ink transfer curve corresponding to x_{max}
k = rate of coverage parameter (m²/g or µm-1 in WF and K equations and g/m² or µm in L equation)
b = immobilisation or absorption parameter (g/m² or µm)
f = free ink split parameter

A = coverage factor
B = immobilisation factor
$\mu_1\sigma_1$ = mean and standard deviation of lognormal distribution of ink covering resistance
$\mu_2\sigma_2$ = mean and standard deviation of lognormal distribution of ink absorption function
n_o = paper related parameter
A_o = flattened fraction
S = slope of linear portion of the transfer curve after x_{max}
Int = intercept of linear portion of the transfer curve after x_{max}
r_2 = overall correlation (coefficient of determination)

Using the GFL printing tester (ink transfer from a hard metal plate) and a letterpress newsink, De Grâce's et al. /22/ found that a rougher newsprint needed more ink to reach the maximum ink transfer point (the end of Region I in Figure 23) than smoother ones (PPS S20 4.15 and 2.5μm respectively). In addition, the maximum value of the fraction of ink transferred was higher (65% vs. 60% respectively). This means that the roughness volume of the rougher paper surface had been filled with ink more slowly, when ink amount increased. With the higher nip pressure, the fraction of ink transferred increased only slightly. Instead, the increasing printing speed from 1.1 to 5.9 m/s had a greater influence on the fraction of the ink transferred. The flow in the capillaries or laterally between the plates is proportional to square root of nip time and pressure (equations (6), (7) and (10)). Thus, the relative difference in the given speeds (1.1-5.9 m/s) was higher than that of the nip pressure variation (10.7-17.8 kN/m). De Grâce et al. /22/ did not agree with Walker-Fetsko equation (5) for the rough newsprint surface. It was also discussed that the ink transfer from a flexible offset blanket follows a different curve than that from a hard metal plate.

Conclusions: The entrapped air and can explain why the maximum fractional ink transfer for the smooth coated grades is below 50% (40-45%), but roughness of newsprint can explain the values above that (60-75%) in laboratory scale printing. In the case of the coated grade, the entrapped air decreases the actual contact area between ink and paper but the actual surface of the newsprint is higher because of roughness, even though the surface is not covered completely. So, the ink transfer with small amounts of ink would not be as highly dependent on immobilising of ink via penetration but on the actual contact area and ink coverage.

4.2.5 Ink location on the surface of paper

Discussing of the results of ref. /23/ DeGrace and Mangin noted: 'Due to the paper surface pores being more open in the direction parallel to the paper surface (x, y) compared to the inside pores, we tend to believe that ink flow (in the printing nip) is limited in the z direction of the paper. The ink then has no other alternative than to fill in all the surface pores up to a saturation point, which is well beyond any practical printing conditions. For instance, the saturation point for a newsprint calendered at a Parker Print-Surf S10 value of 3.0 μm roughness has been calculated to be about 14 g/m^2.'

Helle and Johanssen /45/, and Gregersen et al. /44/ studied with an electron microscope where ink locates on the surface of CSWO printed newspaper. They found that ink is distributed in the micro scale not evenly but depending on the structure of a paper surface (Figure 24). On the top level of the surface structure, they found ink squeezed away to neighbouring depressions or to the area of lower pressure (Figure 25). On the lower level of the surface structure, there were ink droplets here and there on a fibre 10 μm lower than the topmost fibres. Obviously, the impression pressure was very low in this area because they did not find any spreading of the ink droplets over the fibre. The flexible printing nip (rubber blanket and paper) had been conformed sufficiently by nip pressure to carry the ink droplets onto the lower level of the surface structure but there was not enough pressure to spread the ink droplets. They also did not find ink penetrated under adjacent fibres.

In Figure 24 the profiles on the left, the ink coverage in surface depressions can be seen. The surfaces are partly covered by ink but are not filled in. Our study /46/ agrees with the results of Helle et al. Almost no ink existed under fibres, and a clear movement of ink from the topmost fibre surfaces has been commonly seen. Also, no clear ink flow into the surface voids could be seen.

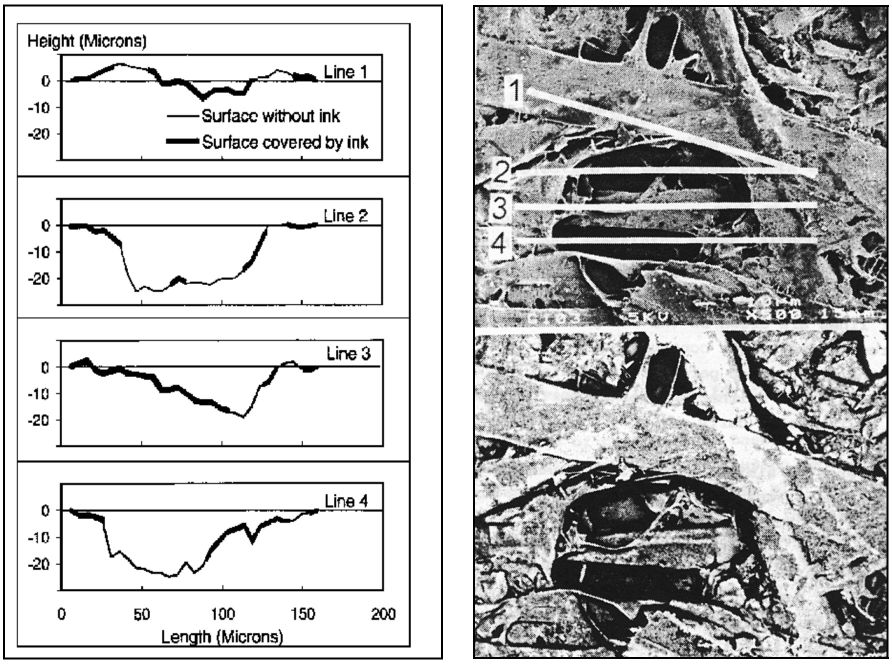


Figure 24. On the left, height contour lines, with ink coverage indicated by bold lines. Back scattering image (BEI) of the same detail on the right, bottom, secondary electron image (SEI) on the top /44/.

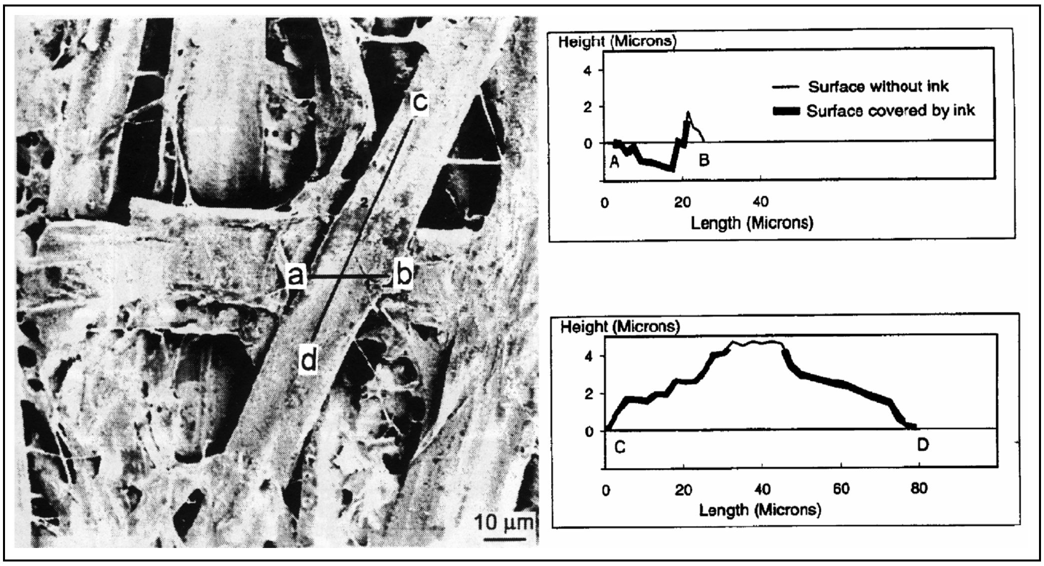


Figure 25. Left: Offset printed detail on newsprint. Ink pigments are seen on the fibres, secondary electron image (SEI). Right: Height contours of the lines a-b (1) and c-d (2). The peaks of the fibre carry no ink. /44/

4.2.6 Ink transfer in 1-colour vs. multicolour CSWO printing

Studies of ink transfer in multicolour CSWO printing are not often published. According to personal information, Frank's /63/ cross sections were made of cyan + magenta CSWO printing. The cross section of newsprint had more penetration than that of the coated grade.

Figure 26 is a cross section of solid black print taken from a daily newspaper. In this case, more sections were made, and using a light microscope, the area where the ink penetration was seen was evaluated subjectively. The area of penetration was less than 1% of the total area (less than 10% of one-dimensional line). Figure 27 is another cross section of 4-colour black print about 250-280% of the tonal area. Much more penetration in the picture can be seen; ink has intruded under the surface fibres. It was also the fact in the other cross sections from the same 4-colour picture. On the other side of the paper in Figure 27, the cyan single-colour printing can be seen. The printing sequence was CMYK (cyan-magenta-yellow-black). So, the cyan ink was impressed in all four printing nips and still we can not see remarkable penetration. Instead, cyan ink very nicely follows the surface profile of paper. /14/

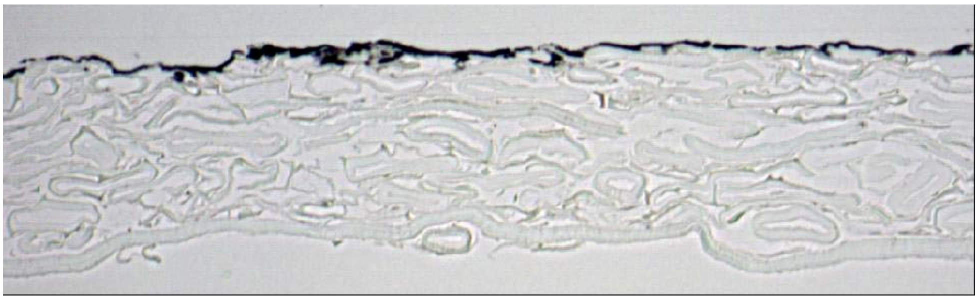


Figure 26. Cross section of a 1-colour picture (black) from a daily newspaper /14/.

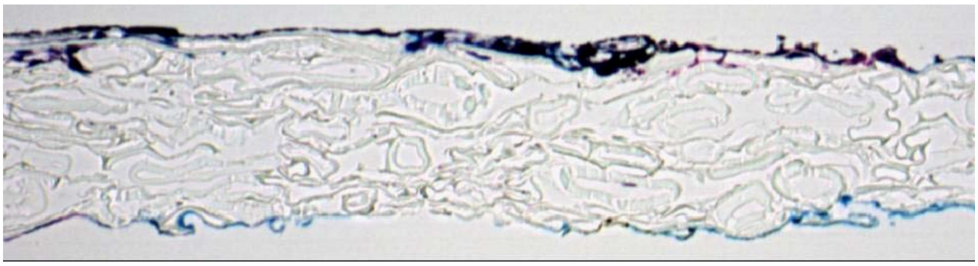


Figure 27.Cross section of a 4-colour picture (black) from a daily newspaper. Under side of paper is cyan printing from the first printing unit. /14/

In multicolour printing, the ink transfer in the first printing unit is aided by nip pressure and the surface contour of both blanket and paper. The following ink transfer to the paper surface has the ability to push the previous inks further into the surface voids, illustrated in Figure 28.

The letters A and B (Figure 28) stand for two surface fibres. The surface rubber (light blue pattern) of the blanket with magenta ink has been penetrated into the void between them. Ink can not contact the paper surface in the middle of the void. In splitting, we can see that a part of the ink film does not split. Fibre A is one of topmost fibres. The nip pressure has squeezed away all ink on it and the ink stays on the edges of the fibre. Fibre B locates on a lower level of the roughness profile and has had some ink on it. The ink amount staying on it depends on the nip pressure and nip dwell time, and the viscosity of the ink.

When the second colour (cyan) is printed the ink can push the first ink (magenta) deeper into the void, but still the surface of the topmost fibre A and the bottom of the void between fibres A and B stays clean of ink. In this case, the ink penetration is not caused by hydraulic pressure in ink but by the kinetic energy of the second printed ink. On the edge where inks magenta and cyan split, or do not, the amount of the transferred ink is dependent on the tack value and shortness of the ink. The viscoelasticity of the ink, decreasing viscosity during shearing, can influence all the phenomena taking place. /14/ The viscoelasticity improves ink transfer /12/.

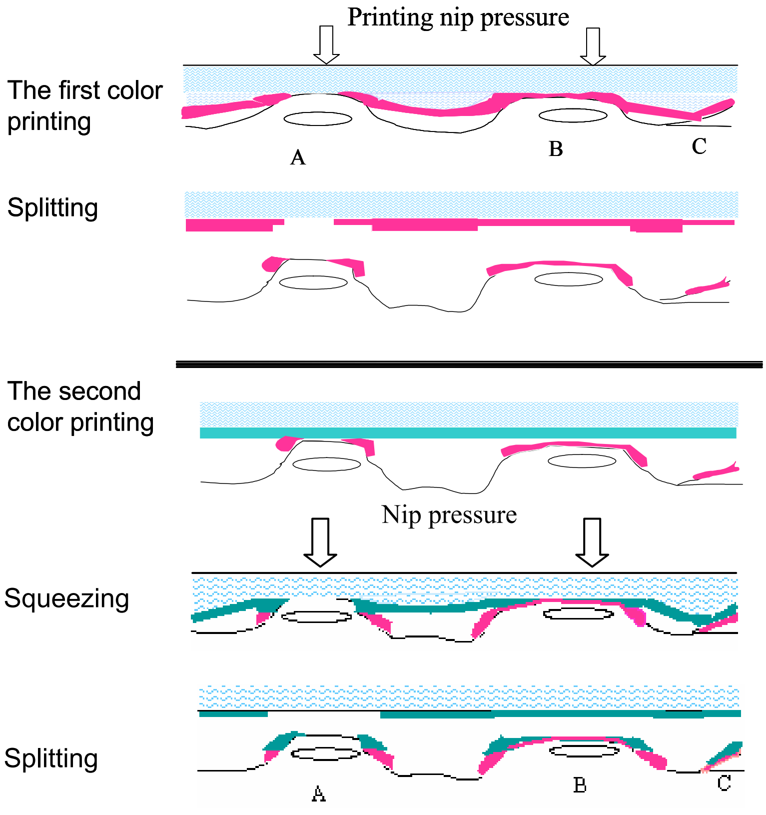


Figure 28. Schematic of multicolour printing. The first printing unit; magenta ink printed on paper. Second printing unit: cyan ink is printed on magenta. The light blue pattern imagines the surface rubber of the blanket.

4.3 Ink setting after printing and before set-off situation

Instead of drying, CSWO inks set via absorption. Set ink does not smear when an element or another paper sheet touches it with pressure, but rubbing can abrade ink away from the surface of the substrate. Setting of ink takes place by time and decreasing of set-off is fastest during first 10 seconds after printing /64/. The time delay needed for certain reduction of set-off depends on the properties of ink and the printing substrate /10, 46/ (Figure 29). Because set-off depends on how well ink has set before the set-off situation, set-off can be used as a measure of ink setting /65/.

Two different ways for ink setting have been discussed: 1) total-ink absorption when ink is moved far from the surface of paper no longer causing smearing /16/, and 2) the solvent separation or the mobile phase separation and absorption when a portion of the low viscosity oils is separated from the ink film and penetrates more deeply into the paper structure, resulting in the ink film becoming stronger /16, 63/.

After the printing nip, there is no external pressure penetrating ink into the capillaries of paper, only the capillary and surface forces apart from the possible short suction caused by elastic resilience of the paper compression /16/. According to Lyne /13/, this may be the last effective movement of the total-ink.

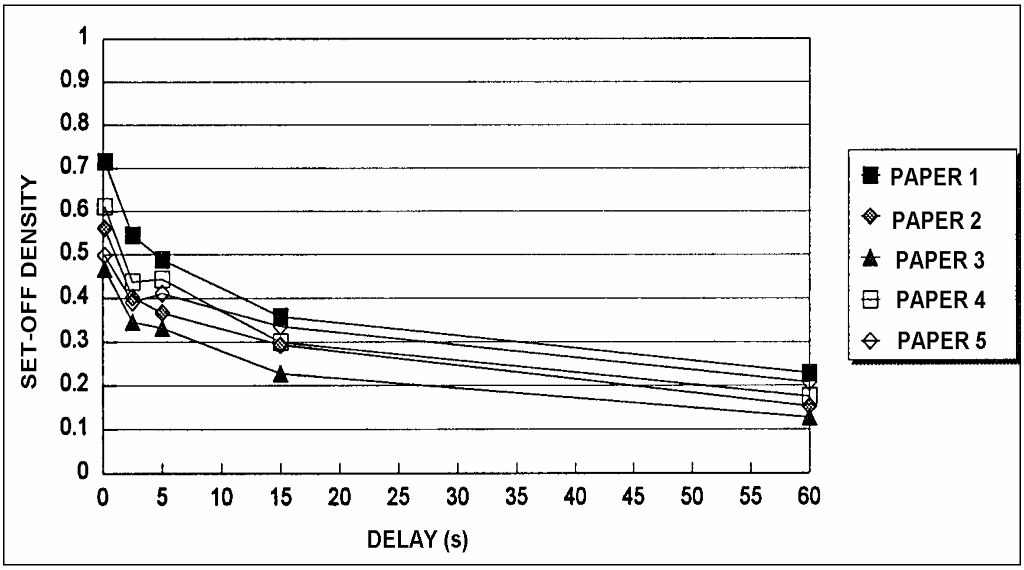


Figure 29. Set-off densities by the delay time (s) with the 5 mill newsprints and one and the same laboratory scale newsink. Prüfbau printing interpolated at 1.0 print density. /46/

4.3.1 Absorption of total-ink by capillary forces

Only ink pigment can represent the total-ink absorption because the vehicle components of CSWO inks have been found to separate from ink and independently to cause print through /55/. In addition, one has to be sure that ink has really been absorbed or penetrated inside the paper and not only being applied deeper on the roughness profile of paper /8/. The ink pigment has to be detected from inside the paper. Only a few ways exist to do that. Cross sections, when one has to make sure that ink does not move from its original place during the cutting on the cross sections with a microtome. Another way is optically to measure print through caused by ink pigment penetration. In this method, the vehicle components applied with ink have to be washed out and then detected optically from the backside of paper showing the print through component caused by ink pigment only. Also, it is possible to use Kubelka-Munk's theory as done in ref. /41/. The two last mentioned methods do not differentiate if the pigment locates inside the paper or only deeper on the surface profile. From the results of these entire methods, it is not possible to see if the ink penetration into paper has taken place in the printing nip or after it.

Oittinen and Lindqvist /16/ have pointed out that Poiseuille's equation for penetration by external pressure and also the expressions of the capillary absorption are valid only if no separation of the easy-flowing components takes place. Some of the measurements had indicated that the absorption in the xy-direction of paper is typically 5 times quicker than absorption in the z-direction. It is thought that liquid can absorb from larger capillaries into smaller ones with the higher capillary pressure leaving the larger capillaries empty /13, 15/. Kent and Lyne /56/ have stated that the pore structure of newsprint is complex and the local geometry of the pore system in paper varies tremendously. As mentioned previously, all the pigment penetration had taken place before 3 s after the printing nip /18/. Also, only seldom has any real penetration been seen; but, ink located on the roughness profile has been seen /8, 14, 43, 44, 45/.

Conclusions: It is difficult to accept the theory of the ink setting dominated by absorption of the total-ink caused by capillary forces after the printing nip. However, theoretically, according to the Lucas-Washburn equation it could be possible that the total-ink might absorb into pores of the certain size and the certain viscosity of ink even within 3 s. There have to be reasons for the infrequent occurrence /8/:

- The flow caused by the capillary forces can continue only as long as the flow is continuous. The smaller amount of ink transferred to paper makes this less probable.
- Ink flow into capillaries is limited in a steric way by larger particles of ink components, especially ink pigments and fillers. The mineral filler particles, and the real ink pigment particles formed by crystals' aggregation can be several micrometers in diameter and can restrict penetration into smaller pores.
- The lowest viscosity components tend to flow most rapidly into such a pore structure (compare paper chromatography). That is why it is expected that the higher viscosity concentrate near the capillary openings prevents absorption ('filter cake effect' /66/).

It is more likely that CSWO ink does not absorb significantly into paper pores after the printing nip.

4.3.2 Solvent separation

Ink setting by solvent separation through absorption is, in practice, well known with the quick-set sheet fed offset inks. The inks incorporate a two-part oil system comprising thin oil, which is readily absorbed through the surface coating of paper leaving the thicker oil, as well as resin and pigment on the surface (Thompson p. 345) /67/. The phenomenon has also been investigated by Rousu et al. /68/. CSWO inks differ to those of sheet fed inks e.g. by having lower viscosity and no drying components but also by having their oil components as solvents. The pore structure of uncoated newsprint is different to that of coated paper grades but newsprint has certain pores as well.

Some studies have proven that vehicle separation from printing ink into the structure of the newsprint can cause 15-60% of the total print through /18, 69, 70, 71/. This means, that also in the case of newsinks, low viscosity oil can release the ink layer and absorb alone into the pore structure of the paper. The oil absorbed reduces light scattering and thus opacity of newsprint, and because the oil does not evaporate at all or very slowly, the effect stays for a long time resulting in print through. The conclusion of oil separation from an ink layer has been made also e.g. in the references /6, 7, 13, 15, 24, 72/. The interaction of ink components is not well known. That is why it is difficult to estimate the absorption speed of low viscosity components into the pore structure of a paper /16/. Flow of vehicle will continue until the capillary pressures in the two materials (ink and paper) become equal /15/.

Larson and Sunnerberg /73/ studied change of the pigment concentration of a commercial and laboratory newsinks removed from paper (newsprint and coated grade) as it happens in measuring set-off. The ink amount transferred to paper was relatively high 4.33 ± 0.05 g/m^2. The pigment quantity was determined optically after removal of the oil component. The amount of the oil component was determined with radioactive iodine, which was chemically attached to triolein (glycerol). The pigment concentration of the model laboratory ink on paper increased during the ink setting time (60 s) from about 14% to 25% whereas the commercial ink did not change at all. However, set-off was taken from the upper part of the ink layer, which changes more slowly than the part nearest the paper surface. Thus, in the beginning of the setting time and of the absorption via solvent (vehicle) separation, the upper part of ink layer does not change. The same thing was noted also in ref. /13/.

4.4 Insufficient ink transfer to a facing sheet i.e. set-off

CSWO printed ink is still wet after 1-2 seconds when it is in the folder of a printing press even after 1-2 minutes in the post press operations. In these situations, the paper surface with wet ink is pressed against a facing sheet when set-off takes place.

Set-off is not very often studied theoretically. Most of the investigations have been prepared as practical printing tests. The results have then been correlated with measurable paper or ink properties. The correlation can be better or worse. If all other printing conditions are constant and only the ink amount is increased, then set-off increases because more wet ink contacts with the facing paper. This is seen with either increasing ink amount transferred /13/ or with increasing print density /64/.

It has also been seen that set-off and rub-off have given inverse results /6, 64, 74/. Both set-off and rub-off are smearing phenomena and thus depending on the potential of ink to cause smear. There are differences in the test methods used for measuring smearing, especially the delay time and the ways to remove ink from the paper surface. Set-off is tested immediately or at least within some minutes after printing while usually rub-off after some hours. Set-off is created with pressure while rub-off combines pressure with abrading /24/. However, it has also been found that one paper-ink combination can give the lowest set-off and rub-off in the same test series/3, 4/.

‘A simple set-off theory’

Bristow and Bergenblad /34/ have presented an equation as ‘a simple set-off theory’ which expresses the set-off value in terms of few factors. The equation has a relation to the ink transfer theory of Walker and Fetsko. Set-off (*S*) has been supposed to be as in equation 12:

$$S = (y - b - h\sqrt{t})rk \tag{12}$$

where y is the total amount of ink transferred on paper, b is an initial ink immobilisation term (the ink amount immobilised in a printing nip) and it is a characteristic of the paper, h is an absorption parameter, and t is the delay time after printing. The surface contact factor r represents the contact area between print and the counter paper. The factor k is a constant combining both the optical and splitting characteristics of the ink.

According to the theory, a part of the ink applied to the paper is immobilised during the exposed time of the printing nip. It is supposed, especially in case of rough newsprint, that during the delay time after the printing nip, a part of the ink or its component absorbs into the pore structure of the paper thus increasing the immobilised ink. This absorption depends linearly on the square root of the absorption time. This part of the ink together with the initially immobilised ink does not participate in set-off. The surface contact factor r allows only a part of the active ink to participate in set-off. This factor contains roughness of both the printed paper and the counter paper. The authors of the theory noted that, if the counter paper is a smooth coated grade its roughness can be neglected. The constant k for the optical and splitting characteristics of ink transforms the printing ink amount to the optical print density, in which relation is supposed to be linear.

The set-off theory presented above has been created for sheet fed printing using the ideas of ink transfer theories. Especially ink immobilisation comes from this theory. Adapting the theory to CSWO printing, and to rough uncoated newsprint can be problem due to the big differences in inks and the paper grades used. The absorption parameter does not separate the cases, if either the total-ink absorbs, or only mobile components of the ink do.

4.5 Paper properties vs. set-off

In the IFRA study /75/, the paper properties were divided into three categories according to the influence on ink setting (set-off and smearing). Roughness / smoothness and oil absorption belong to the category high; sheet density and thickness, medium; and moisture content, formation, and holes and shives etc., low. Karttunen and Lindqvist /6/ have reported that newsprint with low set-off is less compressible, and also rougher and less absorptive than the one giving higher set-off.

In paper making, it is possible to manipulate paper structure using different types of furnish, fibres and fillers. It is interesting that a difference is seen in the set-off values, higher with virgin fibre based newsprint and lower with DIP based fibres /2, 3, 4, 5, 10, 46/. DIP pulp contains a lot of chemical pulp (roughly 30-40%) coming mainly from magazine grades. In addition, the mechanical pulp of the magazine grades is finer than that of the virgin fibre used in the newsprint grades. These differences give DIP based newsprint types e.g. lower bulk /76, 77/. However, it has not been fully comprehended, what the paper properties are, which cause the difference in set-off.

In the following, the properties of paper which look important for set-off are discussed, i.e. pore structure, smoothness, roughness and surface compressibility. The surface of uncoated newsprint contains fibres and fines between the fibres /8/. These two surface types (fibre area and fines area) have different pore structures, and they are discussed in chapters of their own (4.5.1). The influence of the fountain solution on smearing is discussed too and also the measuring methods are taken into consideration.

4.5.1 Pore structure

The immobilisation and setting of newsink have been connected with the pore structure of paper. The porosity of newsprint is usually measured with air permeability methods like Bendtsen or PPS. Gurley Hill measures the air resistance. Cobb-Unger oil absorption test can be performed with different absorption times when it is possible to adjust the test for different paper grades. The typical range of the values for newsprint is 15-25 g/m^2. However, it is about ten times more than the amount of ink applied to paper in the newspaper CSWO printing.

Bristow /38/ developed a device, also known as the ‘Bristow-wheel’ /37/, for studying absorption of different types of oils into paper or board during short absorption times. The similar methods are presented in ref. /37, 39/.

A newer method to measure the liquid absorption into paper is measuring the change of ultrasonic intensity transmitting through paper during the absorption time /78/. The absorption speed can also be measured by following the change of capacitance of paper during the absorption time /65/. For newsprint, the method gives comparable results to the ultrasonic method.

All the absorption methods mentioned above use a large amount of liquid, which is much higher than the amount of printing ink applied to paper in newspaper printing. Thus, the results have to be comprehended carefully when one uses them as an explanation for the printing results obtained.

Mercury intrusion is often used to measure the pore structure of paper. Figure 30 presents an example of the pore structure of newsprint, uncalendered and calendered with two different pressures. The average diameter of the pores is 4-5 μm. Calendering makes the distribution narrower.

The equivalent internal pore diameter of Hg intrusion contains all kinds of pores, as well as gaps and corners. The maximum pressure in measuring, approximately 70 atmospheres (ca. 7 MPa), should cause the remaining void volume to compress to about one quarter of its volume at atmospheric pressure. In such high pressure as needed, the pore structure can change towards finer pores. /56/

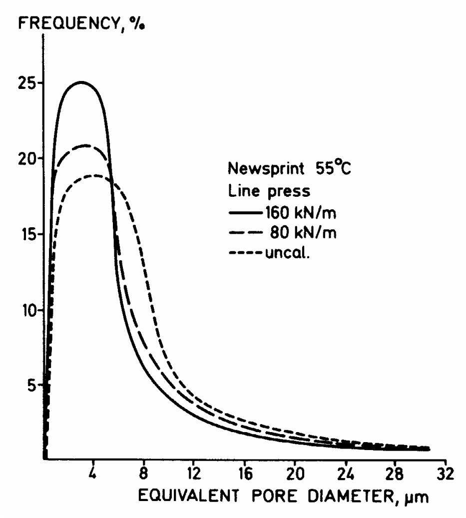


Figure 30. Spectral diagram of equivalent internal pore diameters obtained by Hg intrusion for three newsprint samples, uncalendered and calendered with two different pressures /9/.

The specific surface area of the paper can be measured by the adsorption method of low temperature argon or nitrogen gas i.e. BET analysis (Brunauer, Emmet and Teller) /79/. With letterpress inks, Falter /80/ has found a significant correlation (r = -0.85 for 18 samples) with the BET values vs. set-off measured after 15 s time delay (when a significant part of ink setting had taken place). Porosity measured with mercury intrusion correlated only slightly. This can be explained because the greatest fraction of the mercury intrusion is into larger pores and cavities, which are not important for vehicle absorption while most of surface measured with BET analysis is caused by the finest pore structures, which do perform an important role for ink vehicle absorption.

Bristow et al. /34/ was a little surprised that the results for set-off, after 90 s, and with a sheet fed ink, correlated well with the light scattering coefficient of uncoated paper grades loaded with different filler types, meaning the higher scattering coefficient, the lower the set-off. It was noted that the light scattering coefficient is related to the occurrence of pores having a radius in the 0.1-0.3 µm range.

The fine fillers have a higher number of particles and often also a higher light scattering. The filler particles cause fine capillaries into fines and also between fibres. These capillaries improve ink vehicle separation.

Lyne and Aspler /13/ calculated that all the oil contained by a practical ink layer on paper can not be spread completely as a monolayer on the surfaces of newsprint. The specific surface is ca. 1 m^2/g (Falter /80/ 0.6-1.5 m^2/g). Thus, a part of the oil must also be retained in the finer capillaries in the paper and the ink pigment. The absorbed oil reduces opacity of newsprint. It means that oil adds optical contacts. This is likely made easier by filling the finest capillaries (also in xy-direction) of newsprint suitable for light scattering.

Vehicle (solvent) absorption in the fibre area

In microscopic images, fibre surfaces appear quite closed. Maloney and Paulapuro /81, 82, 83/ have investigated the pore structure of the fibre walls. In drying, a cell wall has collapsed to the density of 1500-1600 kg/m^3, and it does not contain pores. Water absorbs into the fibre wall resulting in swelling, and it can also break the bonds between fibres. Pores up to about 1 µm can exist in the fibres saturated with water. In fibre walls of chemical pulp, pores are larger because of lignin and hemicellulose removal, while in mechanical fibres, pores are smaller. The pores, when they exist, are filled by water. In offset printing, some water is applied onto the paper surface when the fibres directly contact the dampening water emulsified with ink. The water can open pores on the surface of the fibres. However, because the mineral oils are insoluble to water, they are not able to displace water inside the fibre wall. Therefore, the oil absorption into fibre wall pores, filled by water, has to be considered negligible.

It has also been comprehended that the fibre walls could absorb mobile phase of ink in small volumes /28/. The fibres contain fibre pits and also fractures caused by e.g. beating or refining. In the fracture area, pores can be larger than 1 μm /81/. These pores can be opened especially if the fibre is bent suitably, giving an opportunity for the ink vehicle to absorb. However, most of the fibres, which form a part of the surface of paper, have not been bent and they give a closed image in microscopic images, which leads to the conclusion that the fibre pits give the only opportunity for the ink vehicle to flow into fibres.

Fibres have a rough surface. Johnsson and Dettre /15, 84/ have shown that this kind of micro roughness can lead to surface wicking of fluids with intrinsic contact angles of less than 90°. The contact angle of printing ink oil on paper is almost zero. Surface wicking, which is the flow of liquid through the open-sided capillary channels provided by a rough surface, may well account for the migration of low concentrations of oil from newsink through newsprint /15, 85/. The phenomenon is supported by Bascom's /86/ and Haynes' observations /87/. The ink on the surface fibres may set by this way. The idea can be developed further. Via forming filter cake /66/, pigments and larger molecules of the mobile phase of the ink on the rough surface could form another side of the open-sided capillary, which can lead the easiest moving part of ink oil away from the fibre surface and into the paper interior.

Vehicle (solvent) absorption in the 'fines area'

Because there is only limited knowledge of the structure of the 'fines area', some results made of coated grades and sheet fed inks are discussed. Xiang and Bousfield /66/ have investigated ink setting on paper coating measuring the tack value of ink. They created equations for penetration of the ink mobile phase, when the part of ink close to paper coating layer becomes reduced of solvent; it was called the filtercake forming. They found in this case that volume of the ink mobile phase V_p per unit area absorbed by capillaries is proportional to the inverse of the square root of the capillary radius R.

$$(13)\qquad V_p=\sqrt{(4Kt\gamma\phi_f(1-\phi_s)\cos\theta)/\eta\phi_s R}$$

where K is the filtercake permeability, t is time, γ is surface tension of the liquid, ϕ_f and ϕ_s are the solids volume fractions of the filtercake and the original fluid respectively, $\cos\theta$ is the cosine of the contact angle, η is viscosity, and R is the radius of the capillary.

Thus, smaller capillaries of coating give higher absorption, and a quicker solvent separation rate. The results agree with the results reported in ref. /34, 58, 88, 89/. It has to be differentiated between the volume absorption and the absorption speed. If the same volume of pores is shared into a higher number of pores then both absorption speed and volume increases. In practice, this is possible to achieve with paper coating by using finer pigments as observed in ref. /90/.

Conclusion of the ink setting

The majority of the results prove that the solvent separation of ink can explain the setting of the ink on coated grades. Ink also sets on the newsprint surface. Because of the layered structure of paper, there are fine gaps between fibres in the xy-direction. These gaps can be filled with oil separated from the ink layer. The oil forms optical contacts reducing opacity of paper thus adding print through. It has been proven that solvent can be absorbed into the interior of newsprint, but there seems to be a slight statistical probability for the total-ink absorption especially if paper has a very, open porous structure and the viscosity of the ink printed is low. Ink setting on the fibre surfaces might be possible via the open-sided capillaries caused by the micro roughness of the fibre surface.

It can also be agreed that Forsblom's et al. /74/ conclusion that newsprint printed by the CSWO method should not be too open or too closed, and printing ink should penetrate fast enough to prevent smearing however it should not print through to the opposite side.

4.5.2 Roughness

Surface roughness and compressibility have been mentioned as influencing ink transfer, ink requirement and print density. Also, the variations of these properties of paper have been seen to cause print density and set-off variation /50/. In an IFRA study of smearing, it was noted that a high degree of surface roughness is more important for set-off and rub-off than a high degree of filler /3/. Meret et al. /64/ has reported smaller set-off values with rougher and bulkier paper.

For characterizing roughness parameters such as e.g.: roughness volume, wave length distribution, depth distribution, RMS roughness (root-mean-square of anomaly), RMS_A (average of roughness) are used. Also, methods like Mangin and Geoffrey’s /19/ 'printing roughness' have been developed.

The roughness measurement of newsprint is most commonly made with an air leak method e.g. PPS and Bendtsen, or Bekk /91, 92/. The devices based on the air leak method give the average depth of the roughness. It has also been found that during the PPS roughness measuring of newsprint, air loss through the interior of the sheet was 18%, 21%, and 28% of total airflow at 0.5 MPa, 1 MPa, and 2 MPa, respectively. The air loss was found to correlate with normal air permeability tests, Gurley Hill and Bendtsen /93/. The same phenomenon has also been seen with the Sheffield air leak roughness tester /35/. Bichard /91/ has defined the relations of Bekk smoothness with, Sheffield, Bendtsen and Parker Print-surf.

The roughness profile can be measured with the UBM laser profiler, or an interferometric profiler, and with an electron microscope suitable for stereo imaging, or CLSM even under pressure using a compression apparatus. With the profilers, three-dimensional profiles can be created also which can give detailed information of roughness which is important for ink transfer and set-off. Measurements with the profilers show that newsprint commonly has 10-20 µm surface voids. The profiling methods are quite time consuming, and only microscopic areas can be measured; except UBM. /2, 46, 94, 95/

For coated papers and sheet fed printing, Bristow and Bergenblad /34/ have concluded that the set-off tendency is related inter alia to the surface roughness that determines the degree of contact between the print and the recipient paper. These results have also been applied to CSWO newspaper printing /24/.

Mangin and De Grâce /96/ calendered an eastern Canadian newsprint with five different calendering methods to five roughness levels using three temperature levels and both moisturising and not, making 30 samples. The values of bulk and PPS S10 roughness were seen to cross-correlate linearly with only little deviation. Set-off at constant print density had good negative correlation with bulk (and PPS S10 roughness respectively). There were indications that the calendering heat changes the paper surface structure so that the higher temperature tended to cause more set-off at the same bulk or PPS roughness. This kind of tendency could not be seen clearly in Lyne’s /9, 97/ results of the dynamic contact area.

Gratton and Crotogino /98/ have calendered other eastern Canadian newsprint made of 78% ground-wood and 22% chemical pulp with a conventional hard-nip calender, and also hard-nip moisture, and hard nip temperature gradient calender. The both gradient calendering methods gave a glossier and more closed surface in comparison with the conventional hard-nip calendering that had been seen as higher set-off at the same bulk. However, assessing set-off at the same Hunter gloss of paper; both the gradient calendering types gave lower set-off than the conventional hard nip calendering. However, as a rule the higher gloss increased set-off.

Different results to those above, correlating roughness and set-off, were found when a set of 32 samples of North American commercial newsprint types were tested. Print tests were done with a GFL letterpress laboratory device according to the SCAN standard P35:72. No correlation was found between PPS S10 roughness and set-off values at 0.85 print density levels measured by a MacBeth densitometer (Figure 31). /99/

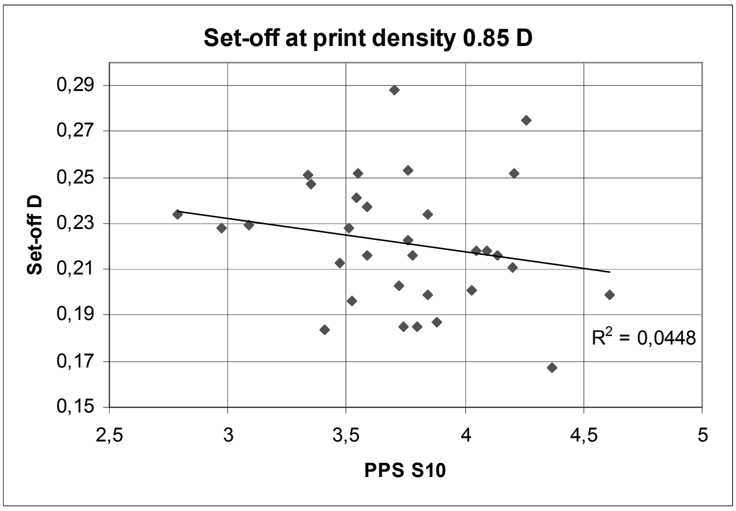


Figure 31. Graph made of Dalphond's et al /99/ results. No significant correlation between set-off and PPS roughness, 32 North American newsprint types tested with GFL laboratory printing tester.

As a rule, higher ink amounts on the same paper increases set-off. In the calendering studies of Mangin and De Grâce /96/, and Gratton and Crotogino /98/, higher roughness means greater ink requirement for achieving the same target print density, however, in these cases the higher ink requirement gave negative correlation with set-off. Meret et al. /64/ and Karttunen and Lindqvist /6, 74/ have also reported a negative correlation between set-off and ink requirement. Larger ink requirement means rougher paper, which leads to lower set-off. In Dalphond's et al. /99/ mill newsprint set, neither air permeability nor roughness and ink requirement for 0.85 D print density had significant correlation coefficients, 0.30, -0.21 and 0.19 respectively. Creating a linear multiregression model of the results, the two first parameters were at a significant level, and also the whole model (Equation 14). In fact, the significance was not great; for the whole model r^2 was 0.381 with $p < 0.02289$. Air permeability improved the significance of the regression model, and ink requirement was not at a significant level but with positive sign.

(14) *Set-off* = 0.196 + 0.000057*(Air perm.) -0.033**(PPS S10)* + 0.062**(Ink requirement)*

Saborin's et al. /100/ laboratory sheets were made of TMP and RTS^{TM} (Low retention - high temperature - high speed TMP refining technology) newsprint pulps to 50 g/m^2. The sheets were calendered in constant conditions to 228 ml/min and 133 ml/min Bendtsen roughness (ws) respectively and set-off printed with IGT laboratory printing press. The counter paper was a coated grade. Bendtsen roughness did not give good correlation with set-off. At the same print density, the rougher TMP sheets had approximately the same set-off densities (D_s) than those of the smoother RTS sheets (0.246 D_s vs. 0.246 D_s after 0.1 s, and 0.141 D_s vs. 0.129 D_s after 6.1 s respectively).

Conclusion of the roughness vs. set-off: If the paper set tested was collected from samples with different calendering but the same furnish and paper making technology, roughness correlated well with set-off. If the paper collection was from different furnish and made using different technologies, the correlation of roughness vs. set-off was hard to find. Generally, a rougher paper seems to give less set-off but there are other properties related to the paper structure which also have an influence on set-off. These properties can be reached making newsprint types of different furnishes and using different paper making technologies.

4.5.3 Contact smoothness (optical)

In Lyne's /9/ experimental study, newsprint type papers were made of mechanical pulps, GW and TMP 100 and 300 ml of Canadian Freeness respectively, mixed with sulphite chemical pulp 80/20. All the 25 paper samples were calendered in different conditions to the Bendtsen roughness range of 108-2121 ml/min. The dynamic contact area range with Lyne's method /97/ was 20-10% respectively. The samples were printed with set-off test using GFL laboratory printing tester and GFL letterpress test ink. TMP and GW obtained set-off on different levels at the short delay times of 0.34 s and 2.7 s. There was a trend towards higher set-off with higher contact area (Figure 32).

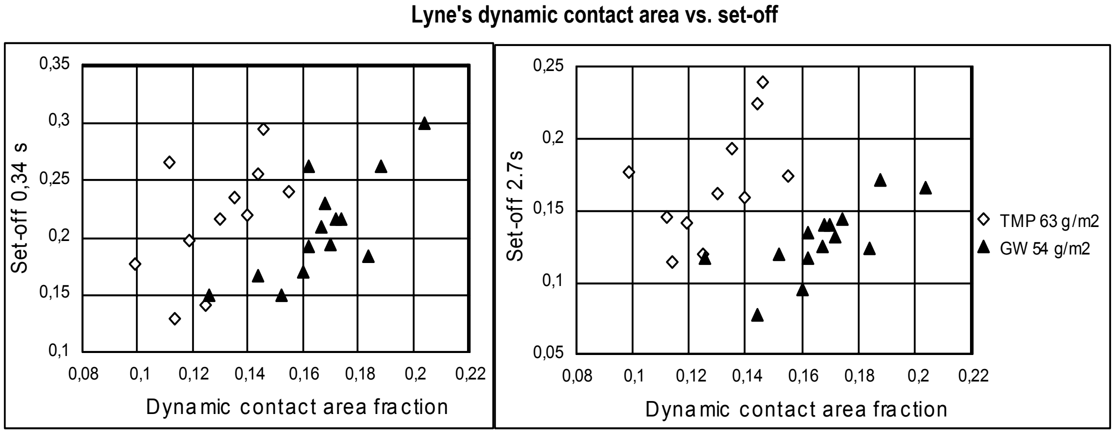


Figure 32. Dynamic contact area vs. set-off density after 0,34 s on the left and 2.7 s on the right, measured by Elrepho reflectometer at 0.85 solid print density. /9/

So, GW had lower set-off values but the dynamic contact area of GW papers was higher than that of TMP. There have to be other factors dominating the set-off values. Lyne supposed that this was caused by decreasing absorbency of paper.

Sunneberg /50/ stressed the dense elements of the paper surface in the case of smearing. The same kind of conclusion was arrived at by Lyne /9/ noting that wiremark, shives, and hard, calendered spots in general appear to contribute most to set-off. These elements are also related to the contact area measured by the optical methods.

4.5.4 Surface compressibility

Like roughness, surface compressibility has also been mentioned as influencing ink transfer, ink requirement and print density. Variation of these properties of paper has been seen to cause print density and set-off variation /42, 50/. Karttunen and Lindqvist /6/ have reported that low set-off newsprint is less compressible.

Compression of paper has a viscoelastic nature, which was found in the different paper grades tested /19, 101, 102, 103/, (thickness compression /104/). In the folder of the printing press, the dwell time for the pressure causing set-off is very short. That is why the viscoelasticity of the surface compression of paper can be important for the set-off phenomenon.

Bristow /105/ has shown that the value of the surface roughness of a sheet made of chemical pulp decreases less by the increasing clamp pressure of the PPS device, than one made of mechanical pulp. Kananen /76/ has done a literature revue of the compressibility of paper. He also measured compressibility of the laboratory sheets made of different mixtures of mechanical and chemical pulps. The compression was divided to the whole paper body and the surface compression. Under pressure, both take place at the same time. The body compression decreases the total pore volume, bulk, and the average of the pore size. However, he mentioned that not all the pores do compress because some pores are located in the shadow of stiff fibres, which do not compress. The surface compression increases the surface contact area and decreases the roughness volume of the paper surface. Bristow /106/ and Kananen /76/ found that the sheets made of mechanical pulp had a higher permeability and they compressed more than the sheets made of chemical pulps. Also, the mixture pulps studied compressed by increasing pressure the more the higher proportion of TMP pulp was mixed with chemical pulp. Similar results were also in ref. /107/. In addition, Kananen's results gave the indication that fibre fines added to a sheet do not control the compressibility of a sheet. The matrix formed by fibres takes the main responsibility for that. In the study, the chemical soft wood pulps and hard wood pulps performed roughly in the same way from the compressibility point of view. Mangin et al. /94, 108/ used a confocal laser microscope with a pressure device. They also found that paper made of chemical pulp compressed less than a mechanical fibre sheet.

Bristow /105/ has created the surface compressibility *K'* calculating:

(15) $K' = -dR/d(\log P)$

where *dR* is roughness change, and *P* is pressure.

Cycling PPS (Model 750) roughness measurements with different pressures and seeing hysteresis he also proved that plastic and elastic components exist in the compression of a paper surface, and that the elastic component is virtually constant (Figure 33). Bristow also found a slight but not significant viscoelasticity, when the time between measurements was 5 s, or 30 s. Roughness values were a little lower with longer time but no longer with higher pressures of 4-7 MPa.

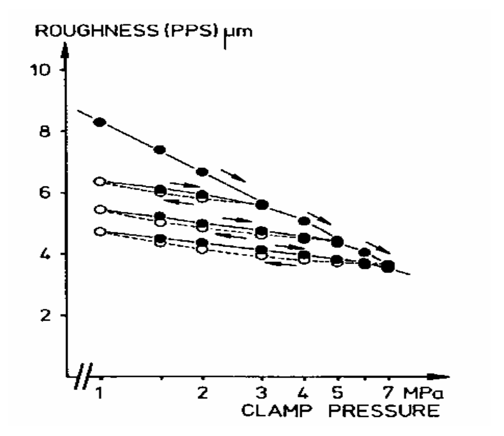


Figure 33. Plastic compression (over line) and elastic deformation (lines below) of the surface of an uncalendered paper. PPS roughness values were measured with modified model 750 and the harder Melinex backing. /105/

Paper compresses in a printing nip and its surface becomes smoother. Karttunen /28/ has described that surface compression as flattening. Mangin and Geoffrey /19/ developed a printing roughness parameter and found it to be linearly related to the logarithm of the printing pressure. The slope of the regression line yielded a compression parameter. The printing roughness was found to correlate well with standard roughness and porosity of the test results. The theory was tested only with one newsprint type laboratory calendered with five different pressures. In this test, the compressibility parameter was found to be independent from the printing pressure however, for rough papers, it was a function of the paper structure and of the nip dwell time (viscoelasticity of paper).

The dwell time of the printing nip pressure is only 1-2 ms. Such short dwell times have not often been used in measuring the viscoelastic compression of a paper surface. Bilsener /107/ has developed a device for the dynamic contact smoothness based on the Chapman method. The dwell time range (time from beginning to the maximum load i.e. the rise time) used was 40, 60, 100 and 160 ms, and the pressure range comparable with the nip pressure in printing 0.9-6.5 MPa. The contact surface area measured from a mill super calendered coated grade with 2.8 MPa was 16.1% and with 5.5 MPa 29% while dwell time was 60 ms. Brecht and Schädler /104/ have indicated that a rise time of pressure approximately 100 ms would be sufficient to reliably predict the dynamic behaviour of paper in a printing press.

Heikkilä /101, 102, 103/ used a KRK laboratory printing press for measuring the dynamic contact area in the printing nip. The picture was taken from an area of 1.5x1.5 mm^2 via a prism located in a transparent printing disc. ‘Printing’ was performed without ink and one picture was taken during one ‘printing’ revolution. The speed of the ‘printing’ was varied between a range of 0-8 m/s. The contact area measured from LWC paper depended clearly on the ‘printing’ speed and levels off about at 1 ms dwell time (Figure 34). Despite a relatively high deviation, the results proved that the surface of the coated papers compress in a viscoelastic way. Heikkilä has also found that the relaxation time range of paper surface compression is comparable to typical dwell times of paper in printing nips. With the same device, another test series was carried out, speed 0-6 m/s /109/. LWC papers gave a similar picture to Figure 34, but the dynamic contact area of SC paper as a function of the speed increased slightly. With MFC grade, there was no such trend. Sizeable variations were also mentioned as a possible explanation for the results. It was recommended to use an impression pressure of the device, closer to the production printing nip pressure, when it could be supposed that this dynamic contact measuring would best correlate with print quality.

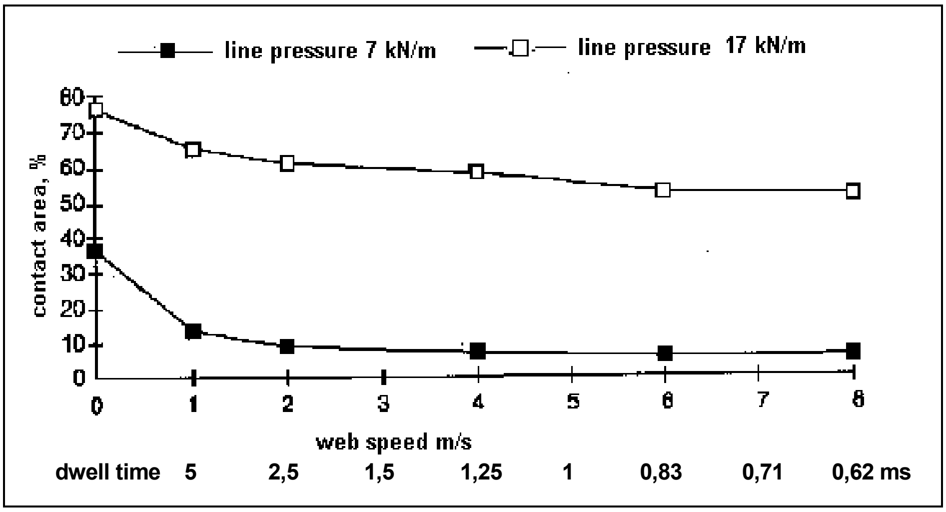


Figure 34. Contact surface of an LWC paper measured with different speeds of ‘printing’ /101/.

Ullman and Qvarnström /110/ have made dynamic compressibility evaluations of nine newsprint grades and one rotogravure paper. They used an IGT laboratory printing press with different pressures in the range of 300-700 N/32 mm (about 2-4.4 MPa with an average nip width of 5 mm). They found that evenness of the solid print area was improved by increasing nip pressure, with soft backing more than with hard backing. In the printing nip during the compression, thick parts of the paper compressed more than the thin parts becoming smoother. The higher the printing pressure the larger the area of the paper surface, which came into contact with the ink on the printing surface.

The results, obtained in ref. /111/ with an IGT laboratory printing press, and with a production scale letterpress newspaper printing press, show that a soft backing (tympan), or soft polymer printing plate with hard backing gave better evenness of print than a hard metal plate with a hard backing. In the production scale printing, it was subjectively detected, that the light halftone dots of the hard metal printing plate used were almost pushed through paper by the nip pressure with low speed (creeper gear). With normal production speed, the phenomenon disappeared. This observation indicates viscoelasticity of the backing but also of the paper in z-direction.

<u>Conclusion:</u> The newsprint paper grades have high absorbency, roughness, and surface compressibility. They perform viscoelastically in the dynamic printing nip conditions that means that the surface compression is greater with the longer dwell time of the nip pressure. Newsprint has also the plastic component of the compression, which can be seen especially during the static pressure.

The surface compression of newsprint in a printing nip increases contact area between ink film and paper surface thus improving ink coverage. On the other hand, the surface compression caused by the pressure in the set-off situation increases contact of the wet ink layer with facing sheet increasing set-off. So, compressibility of newsprint is a contradictory property from the print quality point of view.

4.6 Ink properties vs. set-off

Printability properties: ink requirement for the given print density, set-off for newsinks and sheet fed inks, rub-off, and print through (show through + strike through), are evaluated with the laboratory printability testers like Prüfbau, and IGT. The direct measuring methods mostly give information of runnability of printing inks. With the high shear rate rotational cone and plate viscometer e.g. Haake, it is possible to measure such rheological properties like viscosity, thixotropy, and yield (the minimum amount of shear needed to get the ink to start flowing). The Laray falling-rod viscometer is common in the printing ink industry, and it is used for measuring viscosity and yield. Tack value is measured using a Tack-o-scope or Inkometer. They give different tack values for the printing inks e.g. commonly 100-300 and 5-10 respectively. The Duke water pick up tester is used for evaluating the water emulsification, and usual values are 20-70%. An NPIRI Grind Gauge is used to find the largest particle size of ink, which is a measure of grinding or dispersing result. Colour shades of ink are measured with a spectrophotometer for the four colour process inks. /7, 49, 112, 113/

In offset printing methods, the ink layer is sheared twice, from the plate, and from the rubber blanket, but in the letterpress only once, from a printing plate to paper. Thus, less ink is transferred onto paper in offset and more heavily pigmented inks are needed to achieve a sufficient print density level. If the use of more ink in offset was wanted, the dark tone areas of the printing plate would be filled in by dot gain, which would mean less contrast in the dark tones and decreasing of details in the print. Higher pigment and resin content also means higher tack and viscosity values of the offset inks than those of the letterpress inks. Letterpress news inks are pseudoplastic but not viscoelastic at the shear rates of 10^{-1}-10^{2}, but the polymer resins present in offset ink formulations render them viscoelastic. /13/ In the older literature, the results of set-off are obtained with letterpress inks. The lower viscosity of the letterpress newsinks makes them more sensitive for penetration than the offset inks.

One important property of newsinks from the set-off point of view is the ink requirement for the given print density, especially, when one aims for higher print density levels. Oittinen, and Lindqvist /49/ tested 30 offset newsinks collected from European newspaper printing plants. The viscosities varied a lot, low shear rate (Ferranti 100 1/s) 3,2-37,7 Pas, Tack-o-Scope values (23 ºC, 3 µm, 2 m/s) 43-163, and the particle size, three largest with grind gauge 14-43 µm. Set-off was measured only in a very short time interval of 0,017 s and it was mainly controlled by the quantity of the ink on paper. However, higher viscosity inks implied more set-off, and as it was concluded, due to slower absorption into paper. On the other hand, higher viscosity inks may stay closer to the topmost part of the roughness profile of paper.

In Busk's /71/ study, a set of black commercial CSWO newsinks (from pressrooms) were tested, newsprint was constant. The printability properties of the inks varied at the print density 0.9 D: ink requirement ± 17%, print through ± 16%, rub-off ± 70%, and set-off ± 20%. He concluded that there seems to be no relationship between the short time (0.7 s) set-off and the ink requirement for the newsinks studied. However, in Figure 35 one can see clear correlation between set-off and the ink requirement.

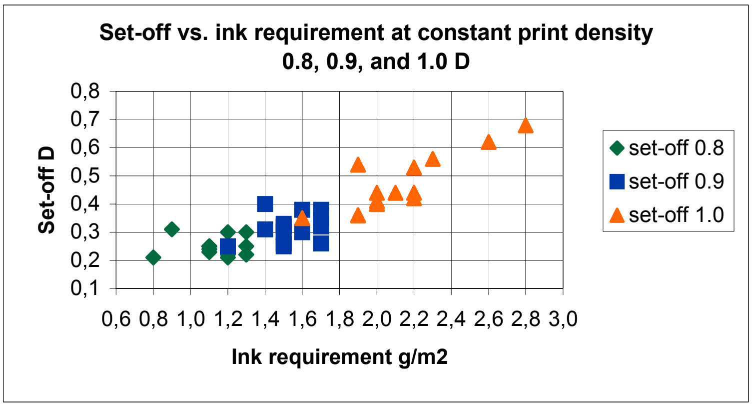


Figure 35. The values of set-off (0.7 s) vs. the ink requirement of the different commercial CSWO newsinks printed on the same newsprint. The set-off density and the ink requirement values are at the print densities 0.8, 0.9 and 1.0 D. The values are picked up from pictures in ref. /71/.

Perhaps Busk has drawn the conclusion from the lower print densities 0.8 D and 0.9 D, which are closer to the normal print densities of one colour printing. On that level, there is either no trend or it is only slight. He has also noted that the increase in set-off with the increasing print density is more pronounced than the increase in rub-off. In addition, Busk did not find any other properties of inks measured to explain the set-off values of different newsinks.

4.7 Smearing vs. fountain solution

The offset printing method applies water as fountain solution to paper, directly and with ink. One can ask if water emulsified into ink could have an influence on set-off. Lie /114/ studied the effect of fountain solution on set-off and on rub-off in newspaper printing. The different fountain solution formulas had significant influence on smearing in the form of rub-off but not on set-off. Adding some isopropyl alcohol (IPA) to the fountain solution did not have any significant effect on either set-off or on rub-off. Instead, a higher pH level of fountain solution (levels 4, 5, and 6) had given less set-off and rub-off. Varying the amount of fountain solution gave a slightly significant effect: negative correlation with set-off but no correlation with rub-off. As a rule, no big changes in smearing with the fountain solution variations could be found. It was also noted that the printing trials with the pilot printing press were of only a few minutes' duration, 2 m/s speed, that no stable emulsification could be reached which might have had an influence on the results.

Oittinen and Lindqvist /16/ have also discussed the emulsification of fountain solution into ink. They have concluded that the emulsion has to be insufficient because the time is only 1-3 ms in the roller nips where the emulsification takes place. 'Such emulsions must be extremely heterogeneous and unstable which to a major extent renders all analysis difficult.'

Water expands fibres during a very short time period /115/. Thus, the dampening water can affect ink setting not only existing in ink but also expanding fibres on the paper surface, and at the same time changing the pore structure of paper.

4.8 Summary and discussion of the literature study

Reasons for set-off in coldset web offset (CSWO) newspaper printing and the results of the apparent set-off in several tests have been the object of this literature study. Set-off is one of the smearing problems of newspaper printing. It also is a problem of sheet fed offset printing, in which it is possible to control with anti set-off powder. This is not possible in the case of newspaper printing. Set-off is created when a newly printed sheet with wet printing ink is pressed against a facing sheet. A part of the wet ink transfers onto the facing sheet. This smearing deteriorates the print quality. It also prevents using high amounts of ink, which are necessary for reaching high print density.

The main materials, paper and ink, are discussed separately. The offset blanket has an important role in ink transfer. This item has been taken into account specifically.

Set-off is considered as a process starting from the ink transfer to paper, continuing to the ink setting after the printing nip, and finally concentrating in the set-off situation itself. Ink transfer in a printing nip determines where ink locates on the roughness profile of paper, and the ink setting how aggressively ink is to set-off. Therefore, also the ink transfer and ink setting are discussed widely.

<u>Newsprint</u>

Newsprint is a rough and porous substrate for printing. There are very commonly voids 10-20 µm deep on the surface of paper. The roughness volume measured by filling the surface of a moving web with liquid is in the range of 5-7 ml/m^2 depending on the pressure exposed to the paper surface. Bendtsen roughness and porosity are roughly 100-200 ml/min and 200-300 ml/min respectively. PPS S10 is usually in the range of 3.5-5 µm, and Cobb-Unger oil absorption (6 s) 15-25 g/m^2. Roughness of newsprint is comprehended as a 3-dimensional profile, which becomes shallower after exposure to a printing nip pressure. This compression depends on the pressure dwell time, i.e. the running time of paper through the printing nip due to the viscoelastic nature of paper. The compression also reduces the porosity of the paper.

<u>Newsinks</u>

Newsinks consist of pigments, binders, solvents and other ingredients; they do not normally contain any drying oil components. The binders are thick oil distillers or bitumen in the case of black ink, but colour inks contain bright oils and resins, which harden with solvent releasing. Solvents are low viscosity non-evaporating mineral oils and vegetable oils. Commonly the CSWO inks have lower viscosity and tack values than those of heatset and sheet fed offset inks. The inks, printed with the CSWO printing method, set by absorption. Letterpress newsinks, which have often been used in laboratory printing tests, are less pigmented and have lower viscosity than CSWO newsinks. The letterpress newsinks are almost Newtonian fluids and CSWO newsinks are non-Newtonian; thus, the inks have different rheology.

Ink transfer

Ink transfer is often discussed using mathematical equations. The most commonly used, are Walker-Fetsko equations: both the simple and complicated versions. The equations have three parameters explaining the ink transfer with ink coverage (smoothness), immobilisation and splitting. It is also concluded that coverage is important with small amounts of ink transferred and the immobilisation starts to be stronger while the whole roughness volume is filled by ink. Also, when all the pores of the substrate are filled by ink, the only parameter of the equation affecting the ink transfer is the splitting parameter. However, these formulas are only theoretical and criticism has been presented against them.

All the movements of ink taking place during printing nip dwell time are controlled by the rheological properties of ink, especially viscosity, tack and viscoelasticity.

Ink coverage: The literature gives a common viewpoint of the ink transfer in offset printing. The viewpoint is that the initial transfer of ink to paper is primarily through hydraulic impression caused by printing nip pressure and followed subsequently by wetting, adhesion and film splitting. However, the penetration of ink into paper pores influenced by hydraulic impression has been argued because in microscope studies, remarkable penetration has only seldom been seen. Thus, that phenomenon can not be the main factor in ink transfer to rough papers with the low amounts of ink used in practice. Instead, the hydraulic impression is found to be the reason for the lateral flow of ink. This lateral flow takes place especially from the topmost parts of the roughness profile to the lower level areas or to voids or cavities which form the lowest counter pressure. The movement rearranges the ink film on the blanket during the dwell time of the printing nip. This is due to the pressure balance. Ink flows towards the lower counter pressure. That is why roughness of paper dominates the ink coverage in ink transfer to newsprint.

Compression of the paper surface by printing nip pressure increases the contact area of ink to paper thus improving coverage.

The influence of the offset blanket on the ink coverage: The compressible offset blanket has a soft rubber surface. The surface of the blanket, especially, conforms partly along the surface roughness of newsprint, creating a larger actual contact surface area of paper and carrying ink on it. The lateral ink flow to voids and recesses also increases the covered area. Compressibility of the blanket can compensate the larger scale thickness variations of paper caused by grammage variation (formation).

The influence of ink properties on the ink coverage: Lower viscosity inks have been found to flow more easily into the surface voids adding to the coverage; also, shear thinning and viscoelasticity of ink help the ink transfer. The higher tack or shortness of ink makes the ink transfer more difficult.

The counter pressure of air located between ink film on the blanket and paper or in the surface pores, voids and cavities is also one factor in reducing ink transfer. The counter pressure of air can be reduced by air flow into the interior of paper with the porous paper grades.

Surface chemistry of ink and paper does not have any major importance in ink coverage because the average nip pressure is much higher than the surface forces of paper and ink (20 kN/m vs. 30 mN/m). However, it has to take into account that the impression pressure in the printing nip against the roughness profile of paper is not constant. The topmost fibres carry the most of the pressure and the lower parts of the profile are exposed with lower pressure. At the "kiss impression" areas, surface chemistry of the elements might also be important. Figure 36 illustrates the pressure variation against the newsprint surface. The block arrow shows the lower pressure area.

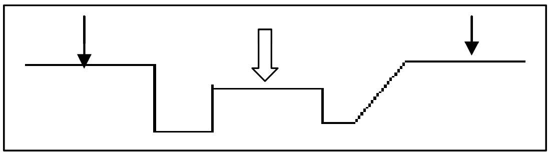


Figure 36. Model is a picture of newsprint surface profile for explaining the pressure variation against the surface in a printing nip. The block arrow shows the lower pressure area.

Immobilisation: According to the ink transfer theory of Walker and Fetsko, immobilised ink does not participate in splitting. It is often understood that the ink is penetrated into surface capillaries of paper and the immobilisation is equal to penetration. However, it has also been defined that ink is immobilised in or on the paper. Thus, not only the capillaries of paper are important but also the surface structure.

Roughness increases the actual surface area of paper. The whole area, which can accept ink by aiding of the conformable blanket surface, is larger than the nominal surface area of paper. This can increase apparently the amount of immobilised ink when the fractional ink transferred has been over 50% for uncoated newsprint. The paper surface also has micro roughness on fibre and in fines areas. The micro roughness of about 1 µm scale can bind more inks than a smooth surface. The capillary structure of newsprint surfaces is complicated. There are larger voids, which can not function as capillaries with the small amount of ink, about 3 g/m^2, offered on the blanket. The capillaries located in the fines area are too small for larger penetration during such a short time in the printing nip. Instead, ink can be penetrated into gaps around fibres if the fibres are suitably located for penetration. After the printing nip, the elastic resilience of paper compression could cause suction for ink into the opening pore structure. However, it has been found that less than 1% of the nominal surface has had real penetration in a normal 1-colour solid print of a daily newspaper.

Splitting of the ink film is the last part of the ink transfer. It takes place just in the outlet of the printing nip. In this stage of the ink transfer, it is thought that cavitation, or back transfer from the larger voids and filament forming control the splitting. These phenomena have less effect on the ink transfer when smaller amounts of ink are in a printing nip.

Based on symmetry, a liquid film splits 50/50 to both surfaces of the opening nip. In practice, the percentage of the offered ink amount is below 50% when the ink amount offered is small and the coverage is not complete. However, it increases to maximum when the coverage also reaches maximum. If the ink amount for transferring is still increased, the fractional ink amount transferred to the paper decreases, and finally evens off to a level, typical for the paper and ink tested. Generally for the smooth coated papers, the maximum stays below 50%, and for the rough uncoated grades like newsprint, the maximum rises above 50%. One reason for the asymmetry in splitting is found to be air between the ink film and paper surface. The effect of this air is larger with the smooth coated grades.

Non-contact areas in splitting: In splitting, the non-contact ink layer above a hole or a void of the paper surface has to be shared from the ink film staying on the paper surface. The shared ink has to stay on the blanket without splitting. Exactly how the ink layer is shared along the edge of the hole depends on ink shortness, and obviously also on the loosening speed or acceleration because ink is viscoelastic. The shorter ink is cut more exactly than the longer ink. That influences the ink transfer and possibly the ink coverage.

Ink amount vs. ink transfer: Ink transfer studies are often done with the range of ink amounts from almost zero to as high as 25 g/m^2. The normal amount of ink CSWO printing is about 3g/m^2, in letterpress printing 5 g/m^2, offered on a blanket or on a printing plate respectively. Those large amounts are far away from practical work and are able to fill all the roughness volume of newsprint. As an example, 14 g/m^2 has been mentioned as the amount needed to fill the whole roughness volume of newsprint. This way to study the ink transfer stresses the higher amounts of ink transferred and the results can give good correlation with an ink transfer equation, although it would not fit well with the practical operating conditions using the small amounts of ink.

Ink transfer in multicolour printing

The image for the multicolour pictures due to coverage and penetration is different in comparison with 1-colour pictures. In the normal newspaper printing, the tonal coverage in a solid 4-colour black area is 240-280%. Much more ink is transferred to the paper that increases statistical probabilities for better ink coverage. Also, more ink penetration has been seen in the cross sections of printed paper. The ink layer printed first on paper is pushed deeper into the surface voids by the following one adding to the coverage area. In addition, the ink squeezed away from a topmost fibre to the edges of it can be pushed deeper into the gap around the fibre adding to ink penetration.

Ink setting

Most of the results have proven that the solvent separation of ink can explain the setting of ink on the coated grades. Ink also sets on the newsprint surface. Because of the layered structure of paper, there are fine gaps between fibres in the xy-direction. These gaps are easily filled with oil that has separated from the ink layer. The oil forms optical contacts reducing opacity of paper thus adding to print through. It is shown that solvent can release the ink layer and then absorb into the interior of newsprint setting the ink, but there seems to be a slight statistical probability for total-ink absorption. This is especially true if the paper has a very open porous structure and the viscosity of the printing ink is low. Ink setting on the fibre surfaces may be succeeded via the flow of oil through the open-sided capillary channels provided by the rough surface of the fibres.

Creating set-off on the facing paper

Paper, ink and the nip conditions (pressure, speed and rubber blanket) play a role in the ink transfer process. Set-off is a similar ink transfer phenomenon, but it also has differences in comparison with the printing nip situation: e.g. in the set-off situation, ink has already started to set and the impression cylinders or pressing elements are different to the offset printing nip.

The fact is that a part of the ink is still wet or non-set when the paper web printed runs to the folder, and even when the folded newspapers reach collectors or the other post press operations. The wet ink can be transferred to the facing sheet, if the ink has been contacted with it. However, ink is squeezed away from the topmost fibres, which can most easily contact the topmost fibres of the facing sheet. In the case of newspaper printing, the facing sheet is normally as rough as the printed one. Because there are two rough surfaces facing each other it is obvious that the contact area without pressure is small. A part of the ink locates on the deeper level of the roughness profile and can be contacted only via compression of paper exposed by pressure of the set-off situation. In this case, pressure in the set-off situation and the compressibility of paper should be important. However, this idea has had only a little coverage in the literature reviewed.

Paper roughness vs. set-off: If the paper set tested was collected from samples with different calendering but the same furnish and paper making technology, roughness correlated quite well with set-off. If the paper collection was made of different furnishes and using different technologies the correlation was hard to find. Generally, a rougher paper seems to give less set-off but there are other properties related to the paper structure which also have an influence on set-off. These properties can be reached making newsprint of different furnishes and using different paper making technologies. In the literature, it was often concluded that porosity is important for ink setting and also for set-off. On the other hand, rough uncoated newsprint is also porous. Specifically, it has been noted that dense small elements on the paper surface like wiremarks, shives, and hard calendered spots in general have appeared to contribute most to set-off. These elements are also related to the contact smoothness of paper measured by the optical methods.

Good properties demanded for paper from the set-off point of view, are high roughness and absorbability (porosity) and low compressibility. In the literature, it is not well explained why newsprint made with a high fraction of de-inked pulp has in many cases given lower set-off than that made of virgin fibres. The higher ash content also, has not been given a satisfactory explanation.

Ink requirement vs. set-off: It has often been seen, the lower the ink requirement of newsprint the higher the set-off. This can be combined with better smoothness, which leads to higher set-off.
When a commercial set of newsinks was the variable and paper and the printing conditions were constant, the higher ink requirement caused no more set-off with low print density levels but with the higher print density levels targeted, there was a positive trend.

Delay time vs. set-off: Set-off decreases rapidly during the first seconds after printing and then the decrease continues at lower speed for more than 10 minutes. It was also measured that after 3 seconds there was no further pigment penetration into the sheet. Because of this, it is likely that vehicle separation causes this decrease in set-off.

With fountain solution, water is applied to paper directly or emulsified with ink in CSWO printing. The different formulae of the fountain solutions studied have had no meaningful influence on set-off, but a higher amount of the fountain solution applied might decrease set-off a little. Increasing pH from 4 to 6 has had a similar effect.

Measuring set-off

Set-off can be measured as set-off density with a densitometer. The SCAN standard suggests using a reflectometer but it is not always possible because of an overly large measuring area of the device. Set-off can be detected also subjectively. Set-off should always be related to the print density of the area, which has caused the insufficient ink transfer. In a laboratory, the set-off property of printing inks and papers can be tested with the laboratory printability testers like IGT and Prüfbau when it is possible to vary ink amount, printing pressure, printing speed, set-off delay time and set-off pressure.

Controlling set-off

Commonly the main reason for bad set-off is excessive ink amounts transferred to paper. Optimising the ink and paper combination and also the ink amounts used can be one possible way to control set-off. Ink loading in heavy 4-colour pictures can be reduced by optimising the use of the under colour removal (UCR). Accepting rougher paper from the same paper machine means a little more ink consumption, but it might give even lower set-off.

4.9 Conclusions

The following issues are not covered well in the literature:

- Defining the rough and complicated surface of newsprint.
- Higher roughness seems to decrease set-off clearly only if the paper set tested is made of one base paper with different calendering efforts. Set-off results measured from the samples collected from different paper mills can hardly be explained with roughness.
- Static vs. dynamic roughness and impact on set-off.
- The effect of the surface compressibility of paper on set-off.
- The pore structure of uncoated newsprint and its impact on set-off are not well known.
- Ink setting on the fibres is not explained perfectly.
- Why newsprint made of de-inked pulp is superior to that made of virgin pulp from the set-off point of view.

5 THEORETICAL ASPECTS FOR THE INK TRANSFER AND THE SET-OFF PHENOMENON

5.1 Surface characteristics of uncoated newsprint for CSWO printing

In the literature section of this study, it was noted that the properties of newsprint important for CSWO printing are especially roughness, surface compressibility, and absorptivity. However, these properties are not defined well enough in order to apply the definition for all cases, papers from different mills and made of different furnishes using different technologies. In Figure 37, we can see an SEM picture of a standard newsprint surface. It is obvious that the surface is rough and porous but this is also inhomogeneous.

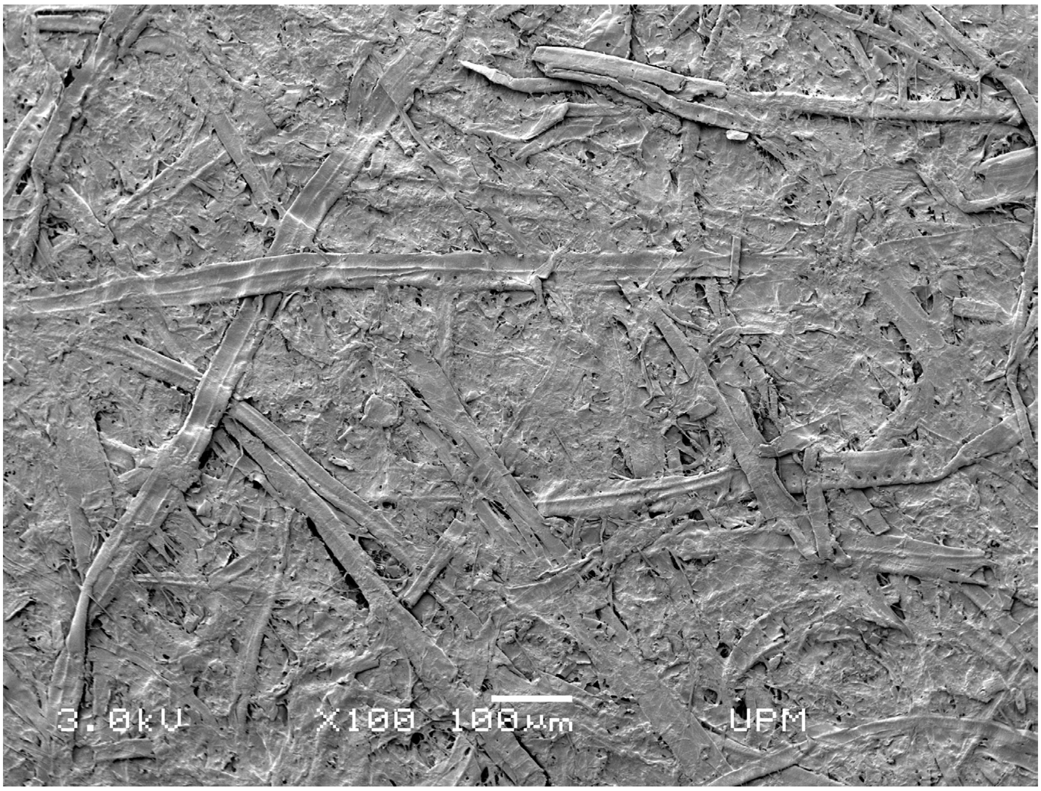


Figure 37. A scanning electron microscope picture of a newsprint surface.

Pore structure of the paper surface is not homogenous. The surface fibres form a matrix oriented more or less in the machine direction. Between the fibres, there are larger or smaller fines areas, which are commonly on a lower level than the topmost fibres. These different area types have been defined as 'fibre area' and 'fines area' /8/. Some fibre pits are visible but they do not dominate the pore structure of the surface. Most of the surface area of fibres is virtually closed to ink components. There are also empty voids and gaps close to fibres. Many of the voids are so large that the small amount of ink applied in a printing nip can not fill them. On the other hand, a part of the 'fines area' seems to be quite closed, but there are also smaller holes. The magnification of Figure 37 is not large enough to see the smallest pores. This porosity is dependent on properties of fines and possible mineral fillers. Luukko /116/ divided the fines of mechanical pulps into two groups: flakes and fibrils. Basically, we can say: the finer the material the better the bonding ability and the finer pore structure. So, the fibrils can form closed surfaces.

Figure 37 is only one magnified view of newsprint. Especially hard machine calendering causes variation to the paper surface because of grammage variation in the formation scale. Therefore, many pictures would need to be seen to make a more accurate comprehension of the nature of the paper surface. These items and influences of the surface characteristics of newsprint on CSWO printing and the set-off phenomenon will be discussed more carefully in the following chapters.

A model roughness profile with ink transferred onto it has been drawn in Figure 38. Although the picture is a rough presentation of the real roughness profile of newsprint, it has been created using the results from the references /44, 45, 46/. Naturally, the micrometers, 5, 10, and 20 µm are not exact values but they give an idea for comprehending what happens in the printing nip and in the set-off situations.

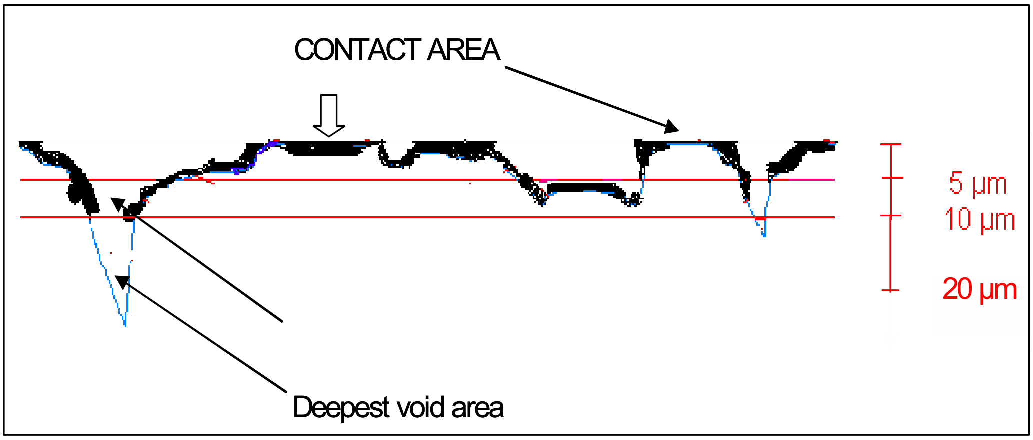


Figure 38. A model drawing of newsprint roughness profile with ink distributed on it /8/.

The roughness profile has been divided into four height levels from the ink transferred and set-off point of view /8/:

1) Contact area: high pressure has pushed ink away from the topmost fibres to the edges of the fibres. This part of the surface takes care of most of the nip pressure.
2) Upper void area: There is ink on this part of the profile and set-off can take place.
3) Lower void area: Ink exists in this area but it does not cover the surface evenly. The ink is transferred with lower pressure than average. There is no set-off from this area.
4) Deepest void area: no ink exists in the deepest parts of the profile, which can extend to 20 µm or even deeper.

The offset rubber blanket helps with ink coverage as explained in chapter 4.2.1. In addition, the ink transfer onto the lower parts of the profile depends on the distance of the topmost parts of the profile. Some of the topmost fibres are collapsed having a groove in the middle of them; block arrow in Figure 38. Ink may stay wet in the groove for a long time bringing potential for set-off. This phenomenon is discussed further in chapter 5.4. The deepest voids should be avoided in paper making.

Water removal in the paper making process can leave some fines in a surface void or it can strip fines away when the void becomes open. In table 3, a fractionation in size for the surface holes of newsprint has been made. These figures only give an idea of the order of the magnitude and in addition, the holes are not normally round in shape.

The maximum size of the recesses functioning as a hole is not measured. It could be dependent on the depth of the hole, the average fibre length, and flexibility of long fibres close to the hole.

The compressible and conformable offset blanket can compensate for shallower recesses especially if they are not steeply shaped. However, many voids close to the surface fibres have a steep form.

Table 3. A fractionation in size of diameter for the surface holes of newsprint /8/.

Capillaries:	< 4 µm	exist in fines area. The pore structure is not well known.
Voids or cavities:	4 - 40 µm	exist often in the angle formed by adjacent fibres. Often non-inked area.
Recesses:	40 - 400 µm	the whole recess often belongs to the fines area fraction. It locates between topmost long fibres or shives but there can also be shorter fibre fractions particularly in the larger recesses.
Specialities: • The gap width around a fibre can be roughly 1-10 µm, and is probably formed by the shrinking of fibres and fines during drying. It does not exist around every fibre. • Fibre pits can allow some ink/solvents to flow into lumen. • Larger recesses between fibre flocks are more porous than the average of the paper surface because of weaker local calendering.		

5.2 Roughness of paper in CSWO printing

Influence of roughness on CSWO printing:

- At the inlet of a printing nip, the rough surface of newsprint forces into the thin ink film on the offset blanket and rearranges the film. This movement of ink improves ink coverage; however,
- Roughness causes poor contact of the thin ink film with paper in the printing nip that means uneven ink transfer, incomplete ink coverage, and a higher ink requirement for the target print density.
- Increasing the light scattering of the print area roughness decreases print density attained. This also means higher ink requirement for the target print density.
- Although roughness of paper increases ink requirement, it also provides hiding places for ink at the lower level of the roughness profile allowing less contact with the facing sheet. This decreases set-off, although the ink amount is larger.
- It has been seen that at the roughness level, 3-5 µm of PPS S10, usual for newsprint, increasing roughness with a lighter calendering load decreases set-off at a constant print density. However, too high roughness weakens print quality like print contrast and evenness.
- Roughness has not satisfactorily explained set-off results attained with the newsprint samples collected from different paper making sites and made of different furnishes. Also, gradient calendering has given higher set-off than the conventional method at a constant print density and at a constant PPS roughness.

So called printing roughness developed by Mangin and Geoffroy /19/ has correlated well with Parker Print Surf measuring when one has used pressures close to the printing nip pressure. Printing was made with an IGT-AIC2 Printability tester and with GFL SCAN standard ink (letterpress). Unfortunately, this method was tested only with one paper calendered to different roughness levels and we know that in this case, PPS correlates well with set-off. Thus, from these results it can not be ascertained whether PPS roughness and 'printing roughness' are also relevant for papers from different mills. Instead, the roughness index developed by Singh et al. /27/ gave good correlation with PPS for different paper grades, i.e. coated, magazine, newsprint and finepapers. This index is based on 50% ink coverage printed with IGT AC2 laboratory printing device and measured by an image analyser. The test gave an indication that the PPS roughness measuring method could be relevant for measuring printing roughness and predicting ink coverage. However, PPS roughness does not explain set-off results of newsprint types from different paper making sites. That is why; the conclusion has to be that set-off requires a more complex explanation than ink coverage.

Compressibility and conformability of the offset blanket improve ink coverage and thus, decrease ink requirement of paper. In the practical set-off situation, the offset blanket does not exist. In the laboratory test printing e.g. with the Prüfbau printing device, there is the blanket on the backside of the printed paper. In this case, it can only compensate for thickness variations of paper giving a more even set-off print. The surface rubber layer of the blanket can not compensate for roughness of paper, as it can in a printing nip.

Obviously, roughness is one of the important parameters for set-off. Although, in particular cases e.g. calendering trials, it can explain almost all the differences of the set-off results, but certain results are too complex to explain with only one parameter. Therefore, also compressibility of paper surface has been mentioned as one possible factor for explaining set-off results. Because compression of the paper surface decreases roughness, making the roughness profile shallower, compressibility is opposed to roughness from the set-off point of view.

5.2.1 Theories and methods to investigate the roughness profile for set-off

Previously, the surface of newsprint from the set-off point of view was divided into 4 areas 1) contact area, 2) upper voids, 3) lower voids and 4) deepest voids. The upper voids and the lower voids are covered by ink (not filled). The upper void area causes set-off but ink hides on the lower void area causing no set-off (Chapter 5.1, Figure 38).

Using a topographical method of an image analyser it might be possible to program the method for calculating and dividing the roughness map into the four height areas presented above. E.g.:

- For image analysis one has to take a topographical picture from the initial print (e.g. Prüfbau), which is at the given print density level, in order to indicate where the ink locates. In addition, one has to take pictures from the corresponding area of the set-off print produced from the same initial print (see pictures in Chapter 6.5.3).
- The image of the initial print is divided into layers in the z-direction by image analysis.
- The picture of the set-off print density is a mirror image from the initial print. The image is transformed to the non-mirror form.
- Then the non-mirror image of the set-off print is subtracted from the image of the initial print. The image of the fibre matrix helps to automatically adjust the image of the initial print and set-off image exactly on top of each other using the image analysis. Now one has two images, one which contains the print areas causing set-off, and the other one containing the areas covered by ink but which caused no set-off and those areas which were not covered by ink at all.
- In comparison of the image of the initial print with the subtracted image, one can realise, from which height levels of the roughness profile set-off was created and where ink stays without causing set-off.
- Correspondingly, the areas not covered by ink and the corresponding depth distributions of the voids can be calculated. This depth distribution should have two peaks, one for contact area i.e. the low depths in which the ink has been squeezed away by printing nip pressure to the lower pressure areas, and the other one containing deep depths where the ink has had no contact with the paper surface.
- The analysis can result in the height distributions of the surface voids for the four depth levels. The height distributions will partly overlap each other because one void can be covered by ink to the same depth level while the other one does not. Correspondingly, one void can cause set-off and the other not depending on the shape of the void and the local structure around it.

The order of the steps does not need to be just as above (adapted from analySIS® 3.0, the EFI module).

Analysing the set-off prints made with the range of set-off pressures (e.g. Prüfbau) it is possible to investigate the effect of the paper surface compressibility on set-off. The effect will be seen in the changes of the height distributions created from the set-off print images. Also, it may be possible to develop a similar equation for set-off from the height distributions and corresponding set-off pressures like Equation (16) created by Mangin et al /19/, which combines roughness and compressibility.

(16) $$R = R_1 + K' * \log P$$

where R is the printing roughness and R_1 is the printing roughness corresponding to P = 1 MPa (log P = 0).

The compressibility parameter K' proposed by Bristow /105/ (Equation (15)) may be calculated for set-off, too.

Using optical or mechanical (stylus) profilometers or microscopes like the confocal laser scanning microscope (CLSM), atomic force microscope (AFM) or scanning electron microscope (SEM) with stereo images it is possible to create topographical maps from the paper surface. However, some of the methods can not find the deepest voids of newsprint and often the area measured is on the microscopic scale or the mechanical profilometers may destroy the paper surface. Most of the methods can not measure the topographical map under pressure. Despite that Mangin et al. /94/ succeeded to create topographical maps from rough papers using CLMS with and without pressing the paper surfaces.

The general topographical equation is of the nth order /94/. For most paper applications like PPS air-leak roughness, the calculated roughness corresponds to the 3rd order roughness (Equation 17).

(17) $$G_3 = \left(\frac{1}{A} \int_0^A z^3 da \right)^{1/3}$$

where G_3 is the 3rd order roughness, A is the measured (nominal) area, da is an element of surface area corresponding to a depth z.

Mangin et al /94/ presented the general equation (18), from which the equivalent surface roughness (ESP) for each topographical map can be calculated.

(18) $$G_3 = \left[\sum_0^{256} D_i^3 * (Ac_{i+1} - Ac_i) \right]^{1/3}$$

where D is the depth of the voids, Ac_i is the normalised cumulative area at intensity i, and every i value represents the certain grey value of the topographical map.

The equation (18) gives opportunity to calculate different layers in the z-direction from the topographical map, when also the layers may be correlated with set-off values finding the suitable values for D_i and Ac_i.

The area causing set-off should be picked out from the topographical map. Combining the picture of the set-off print and the topographical map it might be possible by aid of the fibre matrix to recognize the areas causing set-off from the topographical map and in this way to separate the set-off map and define those D_i and Ac_i values for set-off.

In addition, it is possible to calculate the total set-off area using the inverse of the Murray-Davis equation (19):

$$(19) \qquad A = (1-10^{-D_{INT}})/(1-10^{-D_S})$$

where A is the fractional halftone area (now, representing the set-off area A_{SO}), D_{INT} is the halftone print density (now, representing set-off print density D_{SO}) and D_S is the solid print density.

However, the equation gives only the total set-off area, not the small local areas of which set-off consists. This total set-off area is useless for the topographical equations but it can function as a reference for the set-off area calculated by the image analyser.

5.3 Compressibility of paper in CSWO printing

The compressibility of a paper surface has been discussed mainly in connection with ink coverage. The surface of paper is compressed by the pressure of a printing nip, but it also compresses by the pressing element in the set-off situation. This decreases the roughness of paper and the roughness profile becomes shallower. The compression also decreases the porosity of paper, which also can decrease the probability of ink penetration during the printing nip dwell time.

Compressibility of the newsprint surface is a positive property for print quality, improving print evenness but like roughness, a contradictory property from set-off point of view. It decreases ink requirement (positive point) but increases contacts between ink on paper and the facing sheet (negative point). It has not been ascertained, whether higher compressibility of paper surface via improving ink coverage could decrease set-off more than increase set-off resulting in more contact between the printed surface and the facing sheet. However, the total result of higher roughness in the practical roughness levels of newsprint means less set-off. Analogically to that, less compressibility should mean less set-off because the roughness of paper remains greater under the pressing element of the set-off situation. The pressure in the set-off situation can be varied but the effect of the pressure on the set-off result has not been well known but it is discussed more in chapter 6.2.

Compressibility is usually measured with roughness meters using an air flow method like Parker Print Surf with different pressures. The air flow is the function of the total cross sectional area between the metering ring and the paper surface. Using higher pressure of the measuring device, the cross sectional area decreases, as does the average height of the roughness profile. This average height should be related to probabilities of ink transfer in the printing nip and also in the set-off situations. Thus, theoretically, set-off results should correlate with the PPS compressibility.

5.4 Micro roughness and pore structure of paper for ink setting

Ink setting on the uncoated, rough surface of newsprint is complex and not well defined due to the inhomogeneous pore structure of paper. Some questions can be presented: In which way can the ink on the surface of fibres set? In which way can vehicle component of ink absorb into the interior of paper forming optical contacts inside of the paper and thus increasing print through? What could be the flow along open-sided capillaries in explaining ink setting in CSWO printing?

Ink setting on a fibre

Surface spreading means that liquid is able to flow in an open-sided capillary with the surface forces if its contact angle against the solid surface is less than 90°. According to Bascom et al. /86/ via secondary spreading a liquid film with lower surface tension could carry another liquid film which has a higher surface tension (Figure 39) also over a barrier. In the phenomenon, the liquid with less surface tension first forms a thin film less than 100 nm thick. Then other liquid with higher surface tension could spread over the first film using the difference of the surface tensions. A system was used, where n-hexadecane or pristane (tetramethylpentadecane) with a low surface tension was mixed with purified squalane (hexamethyltetracosane), which has a higher surface tension.

Analogically to that, the vehicle separation of printing inks and ink setting on the fibre surfaces, along with the setting of the ink staying in the middle of the groove of the collapsed fibre may be explained. This would be possible because the aliphatic oil fractions (n-Alkanes) with lower molecular weight have lower surface tension than the fractions with higher molecular weights (Figure 40).

However, according to wetting theory, the surface to be wetted with a liquid should have higher surface energy than the surface tension of the liquid able to spread on it. So, this principle seems to be contradictory to Bascom's et al. explanation for the secondary spreading.

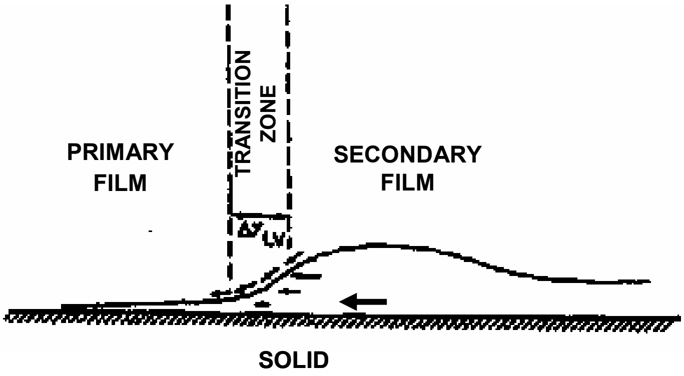


Figure 39. Schematic representation of flow pattern responsible for secondary spreading. The secondary film has a higher surface tension than the primary one that would cause surface tension gradient between the films. /86/

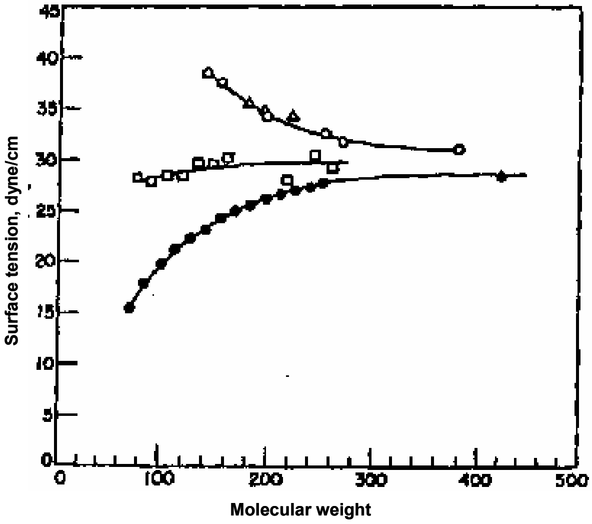


Figure 40. Change in surface tension with molecular weight for various groups of hydrocarbons.● n-Alkanes, □ Alkyl benzenes, ○ Alkyl naphthalenes, and △ Alkyl biphenyls /86/.

Another explanation for the secondary spreading is diffusion because the liquids are soluble with each other. These smaller oil molecules are able to creep along the fibre surface and deeper into interior of the paper. The oil fractions with higher molecule weight can spread more slowly along the film formed by the oil fraction with lower molecule weight. This oil movement sets ink.

The oil components used in CSWO printing inks form distribution of the molecule weights. Following Bascom's et al. /86/ ideas, the oil fractions would form layered film. The lowest molecules would flow on the surface of the printing substrate and the larger molecules on it in the order of the magnitude. Instead, diffusion of the larger molecules to the film formed by the smaller molecules would form a mixture of the molecules after the primary film. Thus, all the oil molecules could flow on the surface of the substrate.

But, why can ink pigment particles not follow the oil spreading, as it has been shown in chapter 4.2.5.

The problem of the ink pigments may be explained by means of micro roughness of fibre surfaces and other surface structures of newsprint, and the open-sided capillary flow. The size of the lines on fibre surfaces can be approximated about 50-100 nm as can be seen in Figure 41. The actual average particle size of ink pigments is 0.5-1 µm and largest agglomerates can be some micrometers. These are not able to flow with the ink vehicle and the oil components can freely flow in the bottom of the small lines existing on the fibre surfaces. On the other hand, the ink pigments with resin molecules can form a 'wall' above the lines when oil components can flow in these formed 'capillaries'. Thus, in that way the oils could also flow between the ink film and substrate.

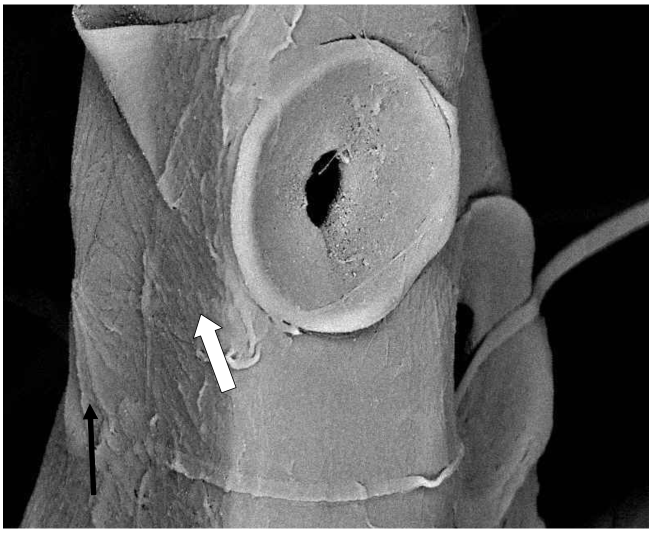


Figure 41. A single fibre surface of mechanical pulp. Arrows show scratches (open-sided capillaries) on the surface. (Picture UPM-Kymmene Valkeakoski Research Centre, 15 kV, 2000x).

Because the micro roughness of uncoated newsprint is complex, these open-sided in-plane capillaries may also exist in the fines area located between the surface fibres. Thus, the oil components flowing laterally can more easily find the small surface capillaries leading into the interior of the paper. The mobile phase of ink leaves ink pigment particles on the places, where they were 'parked' during the printing nip dwell time. This flow of ink oils aided by a 'secondary flow' or by diffusion, and the open-sided capillaries result in the surface wicking of the mobile components of CSWO ink without moving ink pigment particles.

The oil components flow into the interior of the paper by spreading as the 'secondary flow' or by diffusion as explained above. Thus, oils can go into larger capillaries and gaps without filling them. There are also small capillaries and gaps, which can be filled by oils.

5.5 Newsprint made of virgin pulp or of deinked pulp vs. set-off

In several cases, newsprint made of deinked pulp (DIP) has had less set-off than that made of virgin mechanical pulp. It has been suggested that the reasons for that are e.g. higher filler content or higher roughness. It is known that DIP forms a denser sheet and its compressibility is smaller than that of sheets made of mechanical pulps. Earlier, when ground wood pulp (GW) was commonly used for newsprint, it was necessary also to use chemical pulp. Nowadays the developed mechanical pulps TMP and PGW do not need reinforcing at all. But, DIP contains 30-45% chemical pulp and the mechanical pulp fraction is finer coming partly from magazine paper grades. So, today the difference in the properties between the DIP newsprint and those made of the developed mechanical pulps are larger than before.

Higher roughness of DIP newsprint is due to lighter calendering needed for reaching suitable bulk. The smaller compressibility could come from the denser sheet and higher ash content, but attention has to be given to the high chemical pulp content as well. Chemical pulps form denser and less compressible sheets. That is why; the lower surface compressibility of DIP newsprint types is well motivated with the content of chemical pulp. The chemical pulp fibres collapse better than mechanical pulp fibres and in addition, they collapse again after drying when the dampening water has wet the surface fibres in offset printing. It has been found that mechanical fibres more likely keep the round form causing roughening.

The finer surface structure of DIP newsprint in comparison with the virgin newsprint types is based on chemical pulp, finer mechanical pulp, and perhaps the finer filler coming from coated paper grades. This finer structure and at least the same PPS roughness than virgin newsprint give an indication that roughness is more evenly distributed on the surface for DIP newsprint types. The surface might have fewer voids, which extend to the lowest void area and which are not covered by ink as illustrated in Figure 38. This could provide more hiding places for ink, not allowing the contact for ink with the facing sheet in set-off situations, and thus giving less set-off.

This finer surface structure may also form more open-sided capillaries and give a higher specific surface (BET). That helps the surface wicking of the mobile phase of ink improving ink setting.

5.6 Effect of brightness of paper on set-off

The special newsprint grades (MFS) are often of higher brightness level. Then, less ink is required to achieve the target print density. Less ink on the surface of paper gives lower set-off. However, set-off on brighter paper is visually more disturbing.

5.7 Ink properties in CSWO printing

Ink transfer

In the literature, it has been noted that the ink properties: viscosity, tack, shortness, and viscoelasticity are important in ink transfer. Lateral ink flow has been considered important for improving ink coverage on the rough surface of newsprint. Ink penetration takes place more seldom, but it is possible in suitable cases.

From Poiseuille’s equation (9) another equation (20) for calculating the penetration’s depths caused by external pressure has been developed:

$$l = \frac{r}{2}\sqrt{\frac{pt}{\eta}} \tag{20}$$

where l is the penetration depth at the given time t, r is the capillary radius, p is the pressure difference between the capillary ends, and η is the viscosity of the liquid.

Poiseuille’s law is valid if the flow is laminar; i.e. Reynolds's number Re is below 1000 /117/.

$$\mathrm{Re} = \rho \cdot u \cdot d/\eta \tag{21}$$

where ρ is the density of the liquid and u is the flow speed, d is the diameter of the tube and η is the viscosity of the liquid.

In the best case, a liquid like CSWO ink with a viscosity of 10 Pas can flow with the aid of nip pressure in 1 ms into a 4 µm wide capillary to about 10 µm. Equation (20) with the values of the parameters above gives a Reynolds's number $\approx 0.04 \times 10^{-3} << 1000$. Thus, the flow is laminar in such a capillary.

The 2 MPa pressure, close to average printing nip pressure, and 1 ms time have been used in Figure 42 where the penetration by nip pressure has been drawn as a function of the pore radius calculated by equation 20. One can see that the viscosity of ink strongly influences the penetration by pressure. The best case mentioned above is not usual because of the reasons listed in chapter 4.3.1. Instead, much lower viscosity inks like water based flexo newsinks ($\eta \approx$ 0.1 Pas) can flow more easily under the surface fibres /44/.

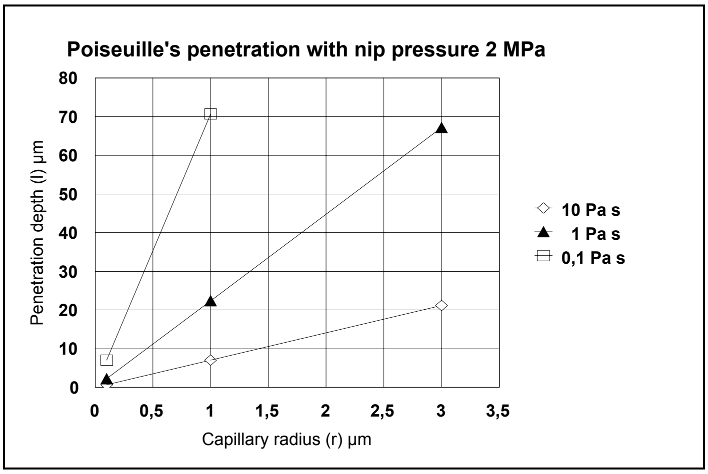


Figure 42. Penetration depths (l) vs. capillary radius when nip pressure is 2 MPa, nip time is 1 ms, and viscosity is 0.1 Pas □, 1 Pas ▲, and 10 Pas ◊ calculated by equation (20) /8/.

The lateral ink flow from the topmost fibres due to the high local pressure in the printing nip is quite common. The situation seems to be close to a 4 µm wide capillary as mentioned before, because the ink layer is approximately 3µm thick and the flow distance is 10-20 µm for the half width of the fibre. This item is discussed more carefully in Appendix 10. In the lateral ink flow, viscosity of ink is important, and ink with a lower viscosity covers the rough surface of newsprint better than ink with higher viscosity. The influence of viscoelasticity and tack of ink on ink transfer is properly discussed in ref. /12/. Viscoelasticity improves ink transfer and higher tack makes it more difficult. Ink can also be 'short' which means that ink forms short filaments in the outlet of a nip; the shorter the ink, the worse the ink transfer.

The temperature of the ink affects its rheological properties. Viscosity of a liquid is dependent on temperature as in the equation (22) /67/:

$$\ln\eta = B/T + C \qquad (22)$$

where B and C are constants for a given liquid and T is the absolute temperature.

Ink temperature in a printing press can vary during the run roughly 20-40 °C. This changes ink viscosity and tack clearly. Ink viscosity as a function of the temperature illustrated in Figure 43 is almost linear in this temperature range, the data from ref. /49/. The relation with $\ln\eta$ and 1/T was not linear. Although the CSWO inks may have changed during last 20 years, the effect of the temperature is of the same magnitude, because similar oil components are in use.

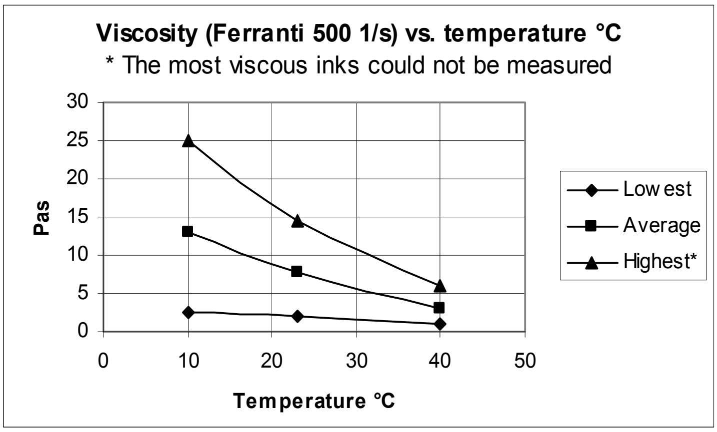


Figure 43. The viscosity range of about 30 CSWO newsink samples collected from different European newspaper printing plants /49/.

In measuring such inks as the CSWO newsinks, there is hysteresis in the stress vs. shear rate curve at a constant temperature. This hysteresis measures e.g. thixotropy of the ink. It means that ink rheology has changed during measuring. The same kind of treatment takes place in an inking train when ink flows through the inking roller system. In addition, there is a short moment when ink stays on the printing plate and on the offset blanket before the printing nip. Therefore, the real rheological state of the ink in the printing nip is unknown.

Ink properties and ink setting

Equation (23) has been developed replacing the external pressure in equation (16) with Laplace's capillary pressure $p = 2\pi\gamma\cos\varphi/r$:

$$l = \frac{r}{2}\sqrt{\frac{2\pi\gamma\cos\varphi t}{r\eta}} \qquad (23)$$

where l is the penetration depth at the given time t, r is the capillary radius, γ is the surface tension of the liquid, $\cos\varphi$ is the cosine of the contact angle between the liquid and the wall of the capillary, and η is the viscosity of the liquid.

This can be used when one evaluates flow of oil components into fine capillaries in paper and also from larger capillaries to finer ones. Because the contact angle of the oils against the fibre material is close to zero, $\cos\varphi$ can be neglected.

E.g. calculating with pore radius 1µm, surface tension 35 mN/m, $\cos\varphi$ 1.0, and viscosity 10 Pas, the capillary pressure causes penetration of 74 µm in 1 s. If this was valid, then the ink would penetrate through standard newsprint but, as it has been seen, this is not a case, and the factors preventing the absorption of the total-ink have to be taken into account (chapter 4.3.1).

Because the mobile phase of ink is separated and the oil components flow into the interior of paper, for ink setting, the properties of the ink components and the interaction between the components are more important than the properties of the total-ink. Different oils, thin, medium and thick oils, and a mixture of them are used in CSWO inks. Every oil component also has a certain distribution of molecule weights. It seems to be obvious that the share of low viscosity oils in the ink could be important for ink setting, because low viscosity oils can more easily spread on the surfaces of the paper structure. This causes the concentration gradient of oils with different molecule weights. The situation creates the diffuse flow of the low viscosity oil component through the ink film towards the paper surface (compare Brown's movement). The thinner the oil is, the quicker it can diffuse through the ink film. In addition, the secondary flow explained in chapter 5.4 could be faster. This tends to quicken ink setting.

The solvent separation is not well understood especially on the rough surface of uncoated newsprint. As a rule, the more easily solvent can release from the ink film the less it can dilute ink resins. The cohesion forces between ink components are against the surface forces of paper materials. Ink components have a high interaction with each other especially if surface active fillers are used in ink. The interactions also cause the ink pigment particles to exist in ink as agglomerates.

As a conclusion, the setting of ink is a very complex process and calculations with the theoretical equations give only a rough idea. In the case of CSWO ink on newsprint, however, this theoretical perusal and the experimental discoveries give the insight that viscous CSWO ink can not flow or penetrate remarkably into surface voids or absorb into capillaries of newsprint in the short time exposed to printing nip pressure. The longer absorption time by capillary forces is strongly restricted by the relatively high viscosity of ink, and larger ink pigment particles, which are not able to follow the oil fraction flowing along the open-sided capillaries. As a rule, ink stays on the places where it is transferred by printing nip pressure. Solvents of ink or thin oil components can separate alone and flow into the interior of paper thus setting the ink layer, reducing set-off and adding to print through. A larger specific surface area of paper could be a positive thing for the ink setting by solvent separation and flow into the pore structure of paper.

5.8 Summary of the theoretical view

The set-off process covers quite totally the whole CSWO printing. It is dependent on ink transfer, setting, and finally on the conditions in the set-off situation.

In ink transfer, the location of ink in and on the roughness profile is important from the set-off point of view. The more ink locates deep in the roughness profile of the newsprint and out of reach of the facing sheet, the less set-off takes place while the sheets are pressed against each other.

By aid of the image of the set-off print and using image analysis and topographical maps it may be possible to measure the height distributions of the surface voids divided into four areas, which are covered or not covered by ink, and whether they cause set-off or not.

There is no splitting of the ink film in the areas, where ink on the blanket does not meet the paper surface. Then, also the ink coverage is created incompletely. This causes loss of light absorption, which has to be compensated with more ink on the contact areas, and this increases the probability for set-off. Instead, good coverage decreases the requirement of ink for the target print density, which is positive for minimum set-off. In addition, lesser ink amounts tend to have a lesser probability for penetration and print through.

Back transfer of ink from the surface capillaries is not so important with such small ink amounts as in CSWO newspaper printing. After the printing nip, compression of paper reverts causing suction force for ink located suitably in the capillaries. However, this phenomenon also seems to be less important because of the low penetration grade.

Ink sets in time, but set-off situations take place after longer or shorter delay times after printing. These times are important for decreasing set-off. The total-ink absorption seems to be negligible mainly because of a high viscosity and small amount of ink. The mobile phase separates from ink film via surface wicking. This surface wicking is aided by surface spreading of the oil fraction with a smaller molecular weight. It has been presented that the secondary spreading, in which the larger oil molecules on the oil film formed by the smaller molecules, could move by the surface tension gradient between the oil fractions. However, this idea seems to be contradictory to wetting theory. Another reason might be diffusion of the larger molecules to the film formed by smaller oil molecules.

Ink sets more rapidly, if the fines area of paper has such a pore structure that solvents of newsink can easily absorb into it. Resins of ink are diluted into oils. According to a common rule of solubility, if a resin is difficult to dilute to the oil of the ink then the solvent release is good and the oil fraction as solvent can release ink film more efficiently. The ink film becomes thinner by leaving mobile phase and it can better lay on the surface profile of newsprint, out of reach of the facing paper in a set-off situation.

In the set-off situation, the most important elements from the set-off point of view are the wet ink film and its contact with the counter paper. It is possible to decrease set-off by offering less a wet ink to the set-off situation and minimizing the probability for the contact between the wet ink film and the facing sheet. Decreasing the amount of wet ink can be achieved by decreasing the ink amount transferred to the paper, speeding up the ink setting, and increasing the time delay before the set-off situation. In practice, all of these are quite difficult to achive. Minimizing the contact between ink film and the facing sheet can be achieved by using rougher and less compressible newsprint and decreasing the load of the pressing elements. Normally, the facing sheet is of the same paper as printed but in laboratory test printing, smooth coated grades are also used, on which set-off is of a higher level. Other cases are mixing a smooth paper grade with newsprint in so-called hybrid printing or in inserting.

Roughness and compressibility of the printed sheet are contradictory properties from the set-off point of view. Smaller roughness in the printing nip, so called printing roughness, is a result of the lower initial roughness and the compression of the paper surface. This gives better contact, and for a good ink coverage, less ink is required. However, in the set-off situation, good contact means higher set-off. It has been seen that a rougher and less compressible sheet is superior in minimizing set-off, even though a higher amount of ink is required for the target print density. DIP based newsprint is superior to newsprint made of virgin pulp. It is often rougher, less compressible and the deinked pulp forms a surface structure for the sheet, which can absorb the mobile phase of the ink.

5.9 Open questions for experimental work

- The order of magnitude of the different factors affecting set-off.
- Compressibility and set-off, little attention paid to that in the literature studied.
- Chemical pulp content of DIP vs. set-off, not published at all.
- Oil components of ink vs. set-off.

5.10 Set-off process analysis

The parameters influencing CSWO printing and especially set-off are collected in table 4 as a set-off process analysis.

Table 4. Parameters and process analysis of the set-off phenomenon. The following aspects need to be taken into account for assessing paper, ink and printing conditions from a set-off point of view /8/.

1. Location of printing ink on and in the surface structure of newsprint and its influence on set-off.

Parameters	**Influence on set-off and other remarks**
Roughness of paper surface and its reduction via compressibility in a printing nip:	The more paper compresses during printing nip time the deeper ink transfers into roughness profile and the less small non-inked areas exist. Less ink is needed for target print density. Less set-off. Print through + and -, because less ink however deeper.
Dwell time in printing nip and viscoelasticity of paper surface:	The longer time in printing nip the more compression of paper surface and the deeper ink is transferred into roughness profile. Less small, non-inked areas exist. Less set-off. Print through + and -, because less ink however deeper.
Impression pressure in printing nip:	The same influences as dwell time.
Flexibility of offset blanket:	Compressible part of the blanket follows variations of paper formation and thickness decreasing the need of nip pressure. It gives more even print in the scale of formation and thus decreases ink requirement. The topmost rubber layer of the blanket is elastic in small scale roughness variations giving more even ink coverage on the scale of the fibre width thus decreasing ink requirement. Conclusion: a compressible blanket has more + than - influences on set-off.
Ink rheology, especially viscosity:	Lower viscosity adds the probability that the total-ink would penetrate into larger surface capillaries decreasing set-off (scaling of capillaries is in table 3). Obviously the nip dwell time is too short for solvent separation.

2. Setting of printing ink by solvent separation and absorption prior to set-off:

Parameters	**Influence on set-off and other remarks**
Dense elements like collapsed fibres, shives and hard calendered spots located on the topmost surface:	Having easy contact with counter paper and preventing solvent separation the elements increase set-off and its unevenness. The hard calendered spots depend on formation of paper and calendering type.
'Fibre area'	Intrinsically closed for oil absorption. The fibres contain fibre pits and also fractures caused e.g. beating or refining. Oils with small molecular weight can flow into the interior of paper along the open-sided capillaries on the surfaces of the fibres.
'Fines area' between surface fibres, and fillers:	The porous areas speed up ink setting by solvent separation decreasing set-off. Fines areas contain capillaries. Strongly bound fines form tighter areas where the capillary absorption of solvent is weaker. Fillers increase porosity.
Setting time of ink before a set-off situation:	The longer setting time the less set-off. It is possible that a little set ink is more prone to smear. As a rule, the beginning of setting time set-off propensity decreases the quickest.
Binder/resin solubility into solvent of ink:	The weaker the solubility the easier solvent separation leading to quicker ink setting, and less set-off.
Viscosity of ink solvent:	Lower viscous solvent can move easier in ink layer by diffusion, progressing solvent separation and thus decreasing set-off.
Viscosity of ink:	A solvent can move quicker by diffusion in lower viscose ink giving faster solvent separation thus decreasing set-off. Nip pressure can push lower viscous inks deeper into roughness profile and into larger capillaries thereby increasing print through.
Ink pigment:	Ink pigment influences solvent separation mostly in steric way. Spherical particle shape inhibits less the separation than the plate shape of ink pigment particles.
Interaction of ink components:	One component can interact with others in the multi component system of a CSWO ink. This interaction is not well understood, especially in the case of solvent separation.

Table 4. cont.

3. Creation of the contact surface between counter paper and ink layer, and ink transfer onto pressing paper during set-off situation.	
Parameters	**Influence on set-off and other remarks**
Compression of the printed paper surface in set-off situation:	The ink layer can reach more contact with the fibre matrix and fines area of the counter paper if the printed paper surface compresses. This increases set-off.
Roughness of counter paper	Less contact with ink less set-off.
Compression of the counter paper:	Increases contact surface and thus set-off.
Pressure and dwell time in set-off situation:	Both increase contact area and set-off.
The stage of ink setting; shrinking and hardening of ink layer	Solvent separation makes ink layer thinner decreasing probability to contact counter paper and giving less set-off. Well set ink does not necessarily adhere, although it contacts the surface of the counter paper.

6 EXPERIMENTAL

6.1 Introduction and targets

Complication of the set-off process has become obvious during the literature studies and the theoretical view. Although there has been a lot of discussion of the subject, several questions have not been explained completely from the set-off point of view:

1. The order of magnitude of the different factors in printing.
2. Compressibility of the paper surface.
3. Roughness.
4. Chemical pulp content of DIP.
5. Differences between DIP and virgin newsprint.
6. Oil components of ink.
7. Ink setting on an uncoated newsprint type.

To find out explanations for the questions above, several test series have been completed and they are reported in the following chapters. The reporting follows the list above starting first by categorising the most important factors of set-off; then continuing by looking through the paper properties and especially the surface compressibility and roughness; then, discussing, why DIP based newsprints are superior to virgin examples from the set-off point of view; and then following the role of the oil component in setting of the CSWO inks. Finally, the ink setting on uncoated newsprint types has been summarised using the knowledge of the literature, this experimental work, and microscope pictures.

In this study, the papers tested represent the following assortments: commercial and laboratory made types. To simplify the set-off situation, single-colour printing has mainly been studied. Multicolour printing brings to the process more variables e.g. higher amount of ink, trapping of other inks onto the previous ink, and 2-7 more impressions. The basic set-off phenomenon, however, remains the same.

For a commercial use of mill papers, it is useful to measure set-off at a constant print density because print density is a controlling parameter of printing. The method chosen for laboratory work is dependent on the targets of the work. The printing test results of this work are discussed at a constant print density and/or at a constant ink amount transferred onto paper.

6.2 Printing parameters and paper properties affecting set-off - Test series 1

6.2.1 Targets

The first target for Test series 1 was to find out what is the order of magnitude of the parameters affecting set-off. In the literature, it has been seen that the newsprint types containing high share of deinked pulp give less set-off. The possible reasons for that (roughness has been mentioned as superior to filler content) were also a point of interest in this test series. Because the set-off print on the counter paper can give information on the set-off mechanism, the same paper as printed and a smooth coated paper were used in this tests series.

6.2.2 Test methods

A commercial paper set, three newsprint grades and two MFS grades were set-off printed with Prüfbau using a commercial newsink under four different printing conditions. The test methods used for paper are listed in Appendix 1 and the set-off testing with Prüfbau is explained in Appendix 2(1-2). Printing nip pressure was constant 10 kN/m and print density values were measured with the non-polarizing densitometer GretagMachbeth RD918. Four ink amounts were transferred to paper. In addition to the normal paper analysis, also the specific porosity analysis, a Coulter oil porometer and a Mercury intrusion, and also BET, the specific surface analysis (BET = Brunauer, Emnet and Teller /79/) were done.

6.2.3 Paper testing and printing results

The papers are described in Table 5 and the paper properties are shown in Table 6. Printing results (Appendix 3(1-4)) were interpolated at constant ink amounts 1.5 and 2 g/m^2 and print density levels 0.9 and 1.0 D* (Appendix 4(1-4). The printing conditions are given in Table 7. Three delay times 0.17, 2.5 and 60 s were used. The shorter delay time typifies the situation in the folder of a printing press and the longer delay time the situation of the mailroom. The results of the pore and specific surface analysis are in Table 9.

Table 5. The commercial papers for test series 1.

Sample	g/m^2	Brightness
1 MFS 1	55	65%
2 News 1, DIP	45	59%
3 News 2, little DIP	45	58%
4 MFS 2	52	71%
5 News 3, virgin	45	60%

Table 6. Paper properties of 3 newsprint and 2 MFS grades, paper sides A and B. The paper samples and analysis in this table are the same as in ref. /10/ analysed by UPM-Kymmene.

Sample	Grammage g/m^2	Thickness µm	Bulk m^3/kg	Sheet density kg/m^3	Ash 550°C %	Ash 925°C %	Emco S-value		Formation g/m²	Unger oil absorption g/m²	
							A	B		A	B
1	55,1	90	1,63	612	3,1	3,0	54	50	3,47	14,1	21,4
2	45,5	63	1,38	722	15,9	14,2	374	290	3,30	13,7	17,1
3	44,2	68	1,54	650	1,6	1,5	46	40	3,13	15,9	17,7
4	52,1	78	1,50	668	1,7	1,7	123	128	3,56	16,3	14,2
5	45,5	75	1,65	607	0,6	0,6	263	245	2,81	22,3	17,7

Sample	Bendtsen roughness		Air permeability ml/min	PPS 5 µm		PPS 10 µm		PPS 20 µm	
	ml/min A	ml/min B		A	B	A	B	A	B
1	142	152	145	5,67	5,17	4,27	4,15	3,44	3,12
2	139	124	219	5,74	5,05	5,10	4,35	4,00	3,44
3	82	87	246	4,49	4,62	3,63	3,61	2,65	2,81
4	75	97	157	4,52	4,81	3,49	3,99	2,99	2,93
5	90	78	513	4,65	4,43	3,79	3,67	2,95	2,83

Sample	Brightness %		Y-value %		Opacity %	Light scatt.co. m²/kg	L* %	a* %	b* %
	A	B	A	B					
1	65,0	65,4	69,7	70,1	95,2	60,4	87,0	-0,07	4,60
2	59,1	58,9	62,8	62,7	95,3	59,8	83,3	-0,71	3,79
3	57,7	57,8	62,5	62,6	93,3	52,8	83,2	-0,59	5,12
4	71,0	70,7	74,1	74,0	91,4	55,8	89,0	-1,64	3,46
5	59,6	59,4	64,1	63,7	93,0	51,1	83,6	-0,12	4,84

Sample	PPS compressibility											
	5/10		10/20		5/20		5-10		10-20		5-20	
	A	B	A	B	A	B	A	B	A	B	A	B
1	1,33	1,25	1,24	1,33	1,65	1,66	1,40	1,02	0,83	1,03	2,23	2,05
2	1,13	1,16	1,28	1,27	1,44	1,47	0,64	0,70	1,10	0,91	1,74	1,61
3	1,24	1,28	1,37	1,29	1,70	1,64	0,86	1,01	0,98	0,80	1,84	1,81
4	1,30	1,21	1,17	1,36	1,51	1,64	1,03	0,82	0,50	1,06	1,53	1,88
5	1,23	1,21	1,29	1,30	1,58	1,57	0,86	0,76	0,84	0,84	1,70	1,60

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*) The print densities are roughly equal to 1.15 and 1.3 D of the densitometer with polarized light.

Table 7. The printing conditions in the test series 1. 'Own paper' is a sample from the same set as the printed paper.

Printing conditions		**1**	**2**	**3**	**4**
Paper	side A	x	x	x	x
	side B	x	x		
Set-off delay	0,17 s (0 s)			x	x
	2,5 s	x	x	x	x
	60 s	x	x	x	x
Set-off pressure	10 kN/m		x		x
	20 kN/m	x		x	
Counter papers	'own paper '	x	x		
	coated grade			x	x

In order to evaluate the importance of the printing parameters for set-off, the Taguchi L_8 model was used, in which 100% DIP paper and 100% virgin pulp paper were chosen for comparison. The printing results were also analyzed by linear (Persson) correlation. Also, regression modelling and conventional comprehension were used whenever suitable. /118, 119/

6.2.4 The order of the magnitude of the set-off parameters, Taguchi analysis

The Taguchi L_8 model is explained in Appendix 5. Parameters for Taguchi analysis are in table 8. The two papers chosen from Table 5 are: Sample 2 'News 1, DIP' and Sample 5 'News 3, virgin'.

Table 8. The parameter values for levels 1 and 2.

Variable	**Parameters for Taguchi analysis**	**Level 1**	**Level 2**
1	Constant ink amount g/m^2	1.5	2.0
1	Constant print density D	0.9	1.0
2	Counter paper	'own'	coated
3	Interaction of variables 1 and 2 (empty)		
4	Paper	DIP (2)	virgin (5)
5	Interaction of variables 1 and 4 (empty)		
6	Set-off pressure kN/m	10	20
7	Set-off delay time s	2.5	60

6.2.5 Results of Taguchi analysis

The effect of the parameters on set-off is presented in Figures 44 and 45, where the results are shown at the constant ink amount of 1.5 and 2 g/m^2 and at the constant print density of 0.9 and 1.0 D. The greater the difference of ETA values between 2 levels of a parameter the bigger is its effect on set-off. A higher ETA value represents a better (lower) set-off value. In the ETA value, y stands for the respective characteristic and N is the number of observations on the particular product.

In Figures 44 and 45, all the parameters studied have a significant effect on set-off (over the dashed lines). The order of the magnitude is only a little different in the cases of the constant ink amount and the constant print density. The exception is the paper type. Its effect on set-off is smaller in the case of constant print density. The list below is an average order of both cases. The better level of the variables from the set-off point of view is mentioned first.

1.	print density	0.9-1.0 D
2.	counter paper	own-coated
3.	paper type	DIP-virgin
4.	time delay	2.5-60 s
5.	set-off pressure	10-20 kN
6.	ink amount	1.5-2 g/m^2

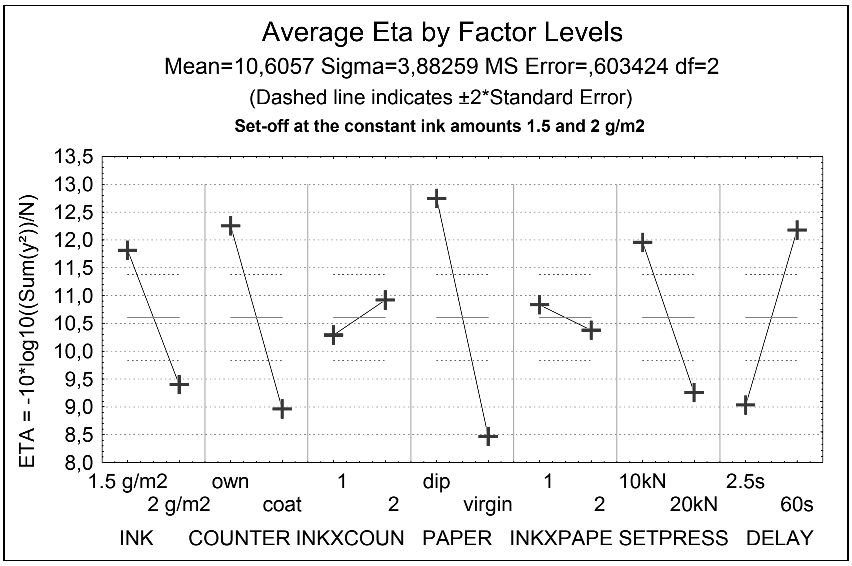


Figure 44. Taguchi analysis of set-off. ETA values, higher number means better (lower) set-off. Ink amount was varied with the other parameters. Parameters: '1.5' and '2.0' are the ink amounts; 'own' and 'coat' are the counter papers; 'dip' and 'virgin' are the papers; 10 kN and 20 kN are the pressures in set-off nip, and 2.5s and 60s set-off the delay times.

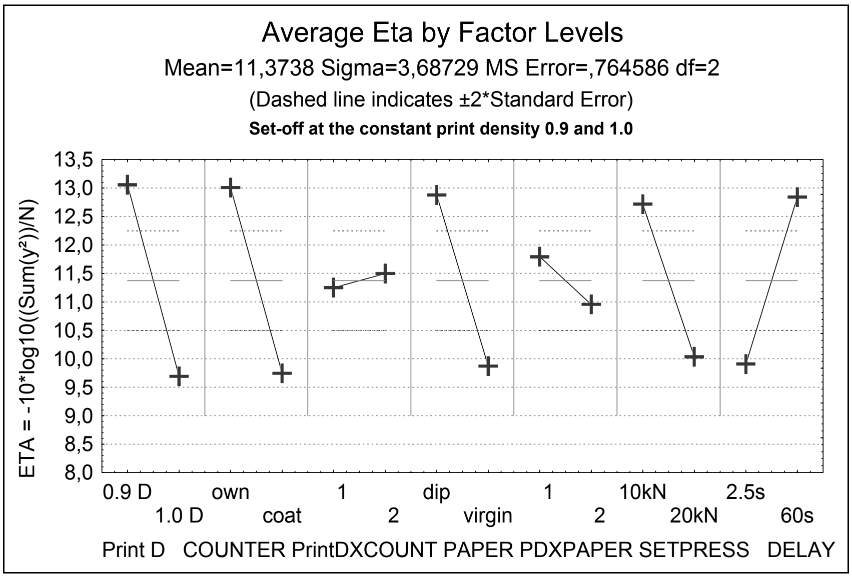


Figure 45. Taguchi analysis of set-off. ETA values, higher number means better (lower) set-off. The print density was varied within the other parameters. Parameters: '0.9 D' and '1.0 D' are the print densities; 'own' and 'coat' are the counter papers; 'dip' and 'virgin' are the papers; 10 kN and 20 kN are the pressures in set-off nip, and 2.5s and 60s the delay times for set-off.

Paper has the greatest effect on set-off when the results are analyzed, using constant ink amounts but print density is most important when constant print densities are used in analysis.

The superiority of DIP paper over virgin paper is decreased from Figures 44 to 45, when constant print densities are used in comparison with constant ink amounts. This is, because the DIP paper needs more ink to reach the target print density than the virgin one, which has increased set-off and decreased the superiority of DIP newsprint. Increasing the print density from 0.9 to 1.0 D, 0.74 g/m^2 more ink is required for DIP paper and set-off (2.5 s) increases 0.12 D, but for virgin newsprint, the figures are lower: 0.46 g/m^2 and 0.10 D respectively. The differences of the values of set-off for 60 s delay are a little smaller but of the same order.

DIP paper needed more ink than virgin paper to reach the same print density. So, there seems to be an interaction between paper and print density, or the ink amount. In the Taguchi method, the parameters analyzed should be independent. It is possible, however, to take into account the interaction between parameters. The method is described e.g. in ref. /120/.

The parameters used here have been arranged into the Taguchi L_8 array so that interaction between ‘paper’ and ‘print density’, or paper and ‘ink amount’, can be found. The parameter demonstrating the interaction is the parameter 5 named 'INKxPAPER' and ‘PDxPAPER’ in Figures 44 and 45 respectively. In both cases with constant print density and constant ink amount, no significant interaction affecting set-off can be seen. According to the theory, parameter 3 demonstrates interaction between parameters 1 and 2 or ‘counter paper’ and ‘print density’ or ‘counter paper’ and ‘ink amount'. No interaction can be found in here, either.

The set-off process analysis argues (Table 4) that by increasing the printing nip pressure less set-off results in via better ink coverage. The required print density can be reached with less ink and less ink means less set-off. In addition, the ink distributed onto the paper surface could locate deeper in the roughness profile being thus less smearing. In an additional test /121/, set-off was tested against nine variables using the Taguchi method / (L_{32}, the larger ETA value the less set-off). The printing nip pressure was also a variable among the others presented in Figure 46 (mechanical pulp freeness, filler type, filler loading percentage, calendering load, ink formula, retention agent, pressure in the set-off nip and delay time).

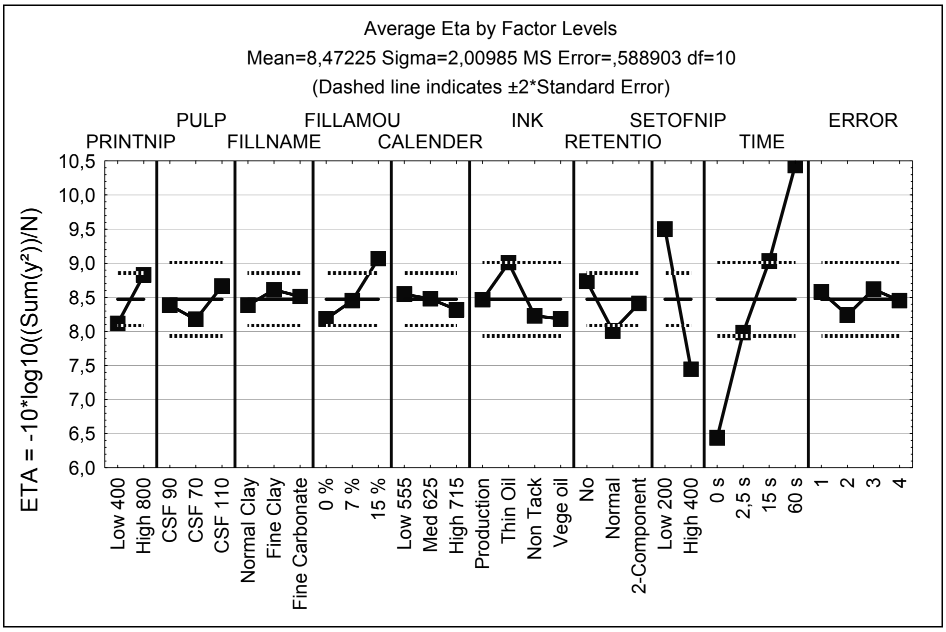


Figure 46. Taguchi analysis of set-off at print density 1.0 D. ETA values, higher number means better (lower) set-off. (Fillname is filler type, fillamou is filler (%), setofnip is pressure in set-off nip, and time is delay time after printing /121/.

The test confirms the earlier results of time delay, the longer delay the less set-off and set-off nip pressure, smaller pressure less set-off. For decreasing set-off, the test also indicates a positive effect of filler of paper and thin oil in ink. The effect of increasing the nip pressure is decreasing set-off. The result is statistically significant at a confidence level of two times standard error.

Strike through and set-off

The strike through, component of print through, is the opposite of set-off from the absorption point of view. That is why, the same analysis as for set-off was done for strike through (Figures 47 and 48).

The same parameters used for set-off (Table 8) affect strike through only a little. (Counter paper, set-off pressure and delay time were 'error' parameters in the strike through analysis.) Parameter 4 'paper' has the best one when the two ink amounts 1.5 and 2 g/m^2 were varied but the direction of the effect on strike through is the same as on set-off: DIP paper is the best. However, when the print density is varied 0.9 and 1.0 D, 'paper' has no significant effect on strike through. Instead of it, the 'print density' almost has a significant effect. The DIP paper needed more ink to reach the target print densities than the virgin paper. That increases strike through of the DIP paper decreasing the difference between DIP paper and virgin paper. So, the effect has weakened below the significant level. Another point is that set-off was measured some seconds after printing, when the ink film is still wet, but strike through the following day. Solvents of ink have had much more time to flow into the interior of paper increasing strike through. Thus, set-off and strike through may be different from the absorption point of view and do not necessarily correlate with each other.

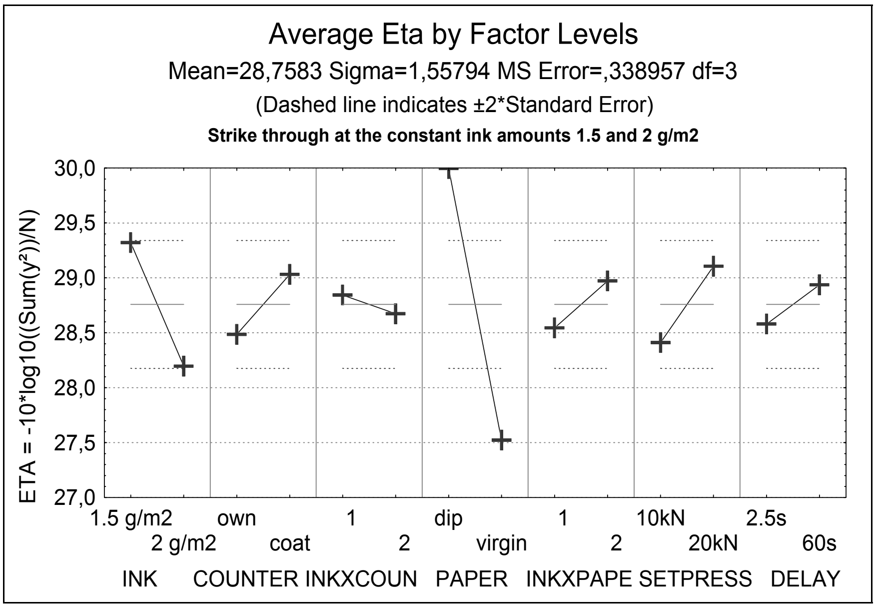


Figure 47. Taguchi analysis of strike through. ETA values, the higher number the better (lower) strike through. The print density was varied with the other parameters. Parameters are as in Figure 44.

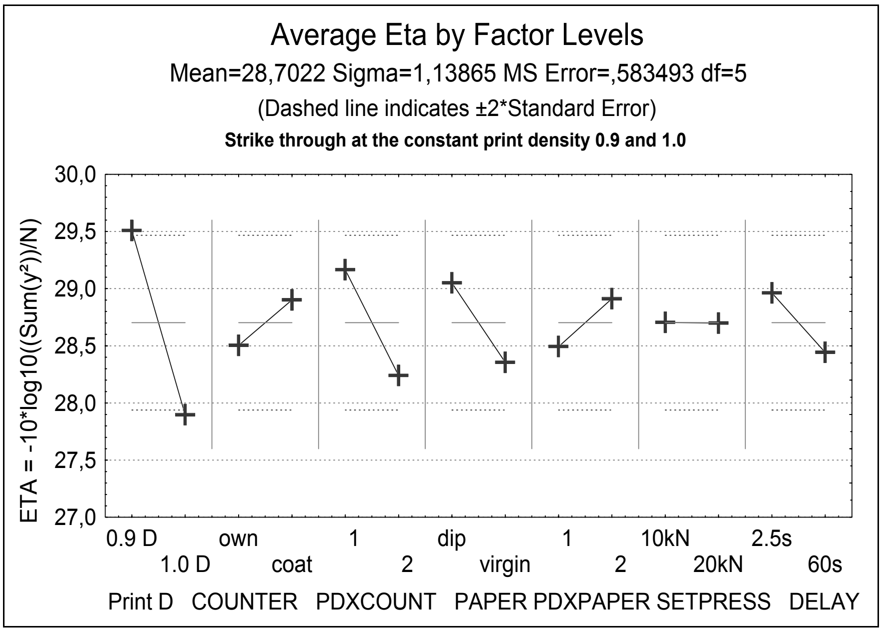


Figure 48. Taguchi analysis of strike through. ETA values, the higher number the better (lower) strike through. The ink amount was varied with the other parameters. Parameters are as in Figure 45.

6.2.6 Paper printing properties vs. set-off

The type of newsprint has been seen to be one of the important parameters for set-off. To clarify the differences between papers, all five newsprint types have been tested and the paper properties have been correlated with the set-off results. The paper properties are shown in Table 6 and the interpolated set-off results are presented in Appendix 4(1-4).

The correlation between paper properties and printing results was analyzed with linear correlation, calculating both sides A and B of papers together. The significant correlation coefficients are given in Appendix 6(2-5). Significantly with set-off correlate (not in all cases):

positively: bulk, thickness, compressibility PPS 5/10 and PPS 5/20, b*-value, print density at the given ink amount.
negatively: ash 550 °C, ash 925 °C, EMCO S, PPS S10, PPS S20, ink requirement.

The ash values form the scatter plot of two points because only DIP news was notably loaded with filler. Because the higher amount of ink increases set-off and many of the paper properties affect both ink requirement and set-off, these are commented on here in the following chapters, when needed together.

Bulk and thickness vs. set-off

MFS 1 and virgin News 3 have the highest bulk and set-off. Also, MFS 1 is the thickest. DIP news 1 with 100% DIP has the lowest bulk, and it is the thinnest and has the lowest set-off. With these connections, the positive correlation of set-off with bulk and thickness can be explained.

Roughness and ink requirement vs. set-off

As it has been found earlier, roughness does not necessarily correlate with set-off specifically in the case of mill papers. In this test series, only the set-off made on the coated counter paper (with half pressure of the set-off nip, and with shortest delay time 0.17s) correlates significantly with PPS 10 and PPS 20. The DIP paper (side A) is much rougher than the others are and it also has the higher ink requirement for constant print densities. MFS 1 (side A) has the same roughness as DIP news 1 (side B) but they have the highest and lowest set-off respectively at constant ink amount transferred. Because MFS 1 is brighter than DIP news 1 it required less ink for the constant print density. Thus, the set-off value of MFS 1 is closer to DIP news 1.

Compressibility and ink requirement vs. set-off

The compressibility of the paper surface has been calculated from PPS roughness values with different clamp pressures of the PPS device. The relative compressibility PPS 5/10 has the best correlation with set-off values interpolated at a constant ink amount 2 g/m^2. In Figure 49 on the left hand side, it can be seen that the other papers except the DIP news 1 shows a lesser trend.

When set-off is interpolated at a constant print density (Figure 49 on the right), the difference is smaller due to inter alia higher roughness of the DIP news 1 and the higher brightness of the MFS samples. Good compressibility improves contact in the printing nip, when the target print density can be reached with less ink. Less ink means less set-off. In spite of that, the DIP news 1 with the lowest compressibility and highest ink requirement has the lowest set-off.

One reason for the low set-off of the DIP news 2 is obviously its low compressibility, which allows less contact between the printed area and the counter paper in the set-off situation.

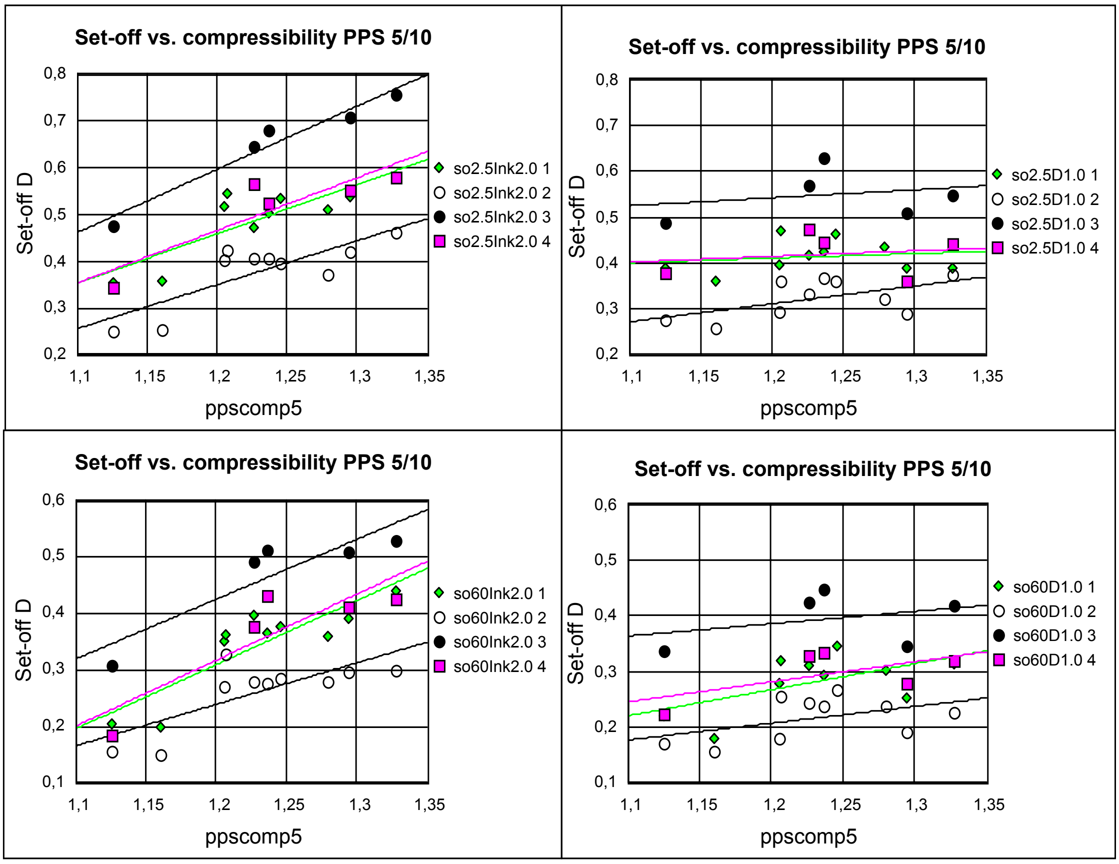


Figure 49. All papers 1-5, printing conditions 1-4 (Table 7). On the left: set-off (so) at the constant ink amount 2.0 g/m^2; on the right: set-off at the constant print density 1.0 D. Set-off delay time 2.5 s is in the pictures above and 60 s below; paper sides A and B at the printing conditions 1 and 2, and the side A at the printing conditions 3 and 4. DIP paper has the lowest set-off values with lowest compressibility.

Brightness, Y-value, L*a*b* and ink requirement vs. set-off

In this test series, the optical properties of the papers do not correlate well with set-off. The values a* and b* have significant correlation only diffusively and weakly. Brightness, Y value and L* value have no significant correlation at all. The paper samples tested have an extensive range of brightness (57.7-71%), which fits in approximately with 15% higher ink requirement for the sample with the lowest brightness. Basically, the brighter paper requires less ink for a target print density. If the surface structure is the same for the papers compared, the brighter one has less set-off in the case of the smooth, coated counter paper. Instead, if the same paper as the printed one ('own paper') is used as the counter paper, the effect of the higher brightness is partly compensated. This is illustrated with an example in Figure 50.

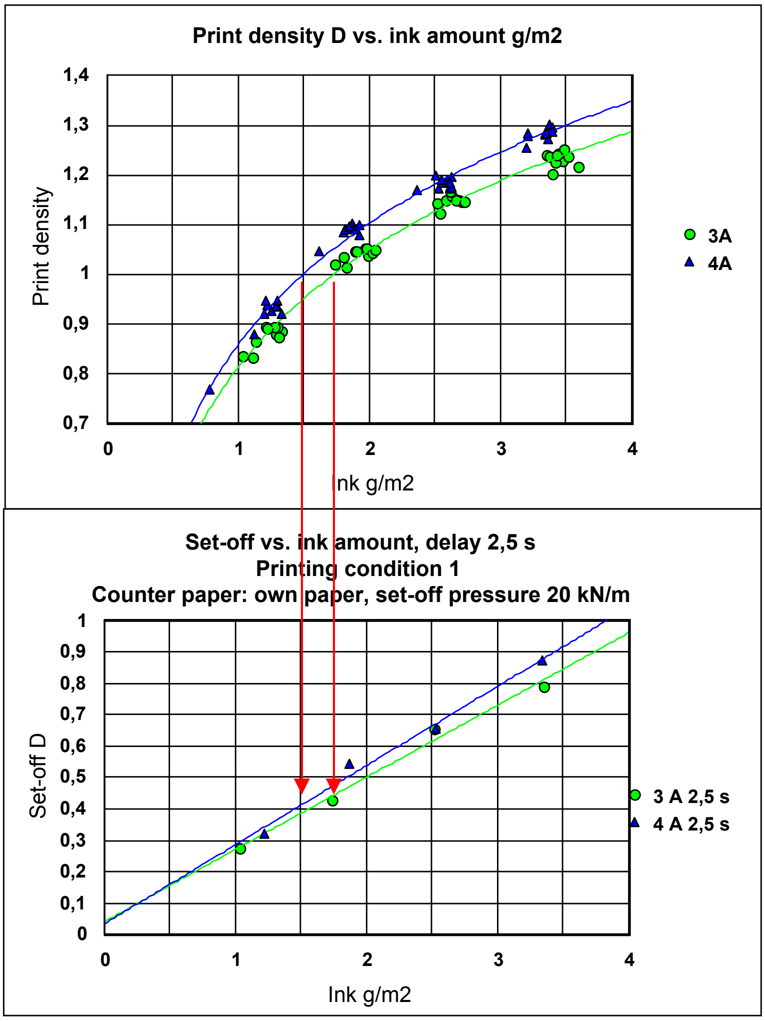


Figure 50. The sample 4 A has the lower ink requirement than the sample 3 A because of the higher brightness (inter alia), but set-off is about the same at the constant print density 1.0 D.

That is, because the densitometer is adjusted to zero for both set-off and print density on the unprinted papers, which are the same in both the printed paper and the counter paper. The densitometer measurement compensates the decrease of the set-off only partly because less ink is needed with the brighter paper and the relation between ink amount and print density is not linear but logarithmic, but set-off is practically linear as a function of the ink amount transferred in a printing nip.

Brightness does not correlate significantly with set-off because the newsprint with 100% DIP has low brightness and low set-off. This compensates for the higher brightness of the MFS grade, which also has lower set-off.

Absorptivity, pore structure and ink requirement vs. set-off

In the Taguchi analysis, it was noted that the time delay between printing and a set-off situation is an important factor for reducing set-off. Among the paper properties measured, only EMCO S represents absorption in the list of the significant variables, and the effect is 'the right', the quicker absorption the less set-off. These correlations are better with constant ink amounts than the constant print densities, average coefficients are -0.79 and -0.52 respectively. But, EMCO S correlates significantly or almost significantly with the 'zero' delay time 0.17 s as well. This is too short a time for ink setting. Thus, the correlation may be explained with the cross-correlation between EMCO S and roughness and compressibility. Cobb-Unger oil absorption has correlation with set-off only in two cases and the effect is 'wrong' or positive. Bendtsen air permeability does not correlate significantly with set-off at all, and also the trend of that is 'wrong' for ink setting.

Pore size distribution measurements

Because of the bad correlation of Cobb-Unger and air permeability with set-off also porometric measurements were made. Pore size distribution was measured with a Coulter oil porometer and with a Mercury porometer (Micrometrics Pore Sizer 9300). In addition, BET, low temperature nitrogen analysis for specific surface was also performed (BET = Brunauer, Emnet and Teller /79/). The results are in Table 9 and 10.

Coulter oil porometric measurements do not provide any explanation for low the set-off values of the DIP paper. The BET value of the DIP paper is clearly the highest. The BET values in Table 9 are close to the values of Falter /80/ 0.6-1.45 m^2/g. In the Hg intrusion, the DIP paper has a slightly higher number of small pores and less large pores.

Table 9. Coulter oil porometer and specific surface (BET) of the five paper samples.

Sample	**Minimum, average µm**	**Maximum, average µm**	**Median, average µm**	**Standard deviation µm**	**Specific surface BET m^2/g**
1	1,3	6,0	2,6	0,1	1,1±0,2
2	1,1	4,0	2,1	0,2	2,4±0,2
3	1,0	4,0	1,8	0,1	1,0±0,2
4	0,9	4,0	1,7	0,1	not measured
5	1,0	4,0	1,8	0,1	1,3±0,2

Table 10. Hg intrusion measurements of the five paper samples.

Sample	**Grammage g /m^2**	**Hg intrusion, diameter of pores**				
		5...2,5 µm	**2,5...1 µm**	**< 1 µm**	**Cumulative cm^3/g 0,01-10 µm**	**Median µm**
1	55,1	0,15	0,20	0,16	0,53	3
2	45,5	0,11	0,14	0,15	0,42	2,5
3	44,2	0,08	0,19	0,13	0,42	2
4	52,1	0,15	0,21	0,13	0,53	2
5	45,5	0,21	0,20	0,09	0,53	3,5

The BET and Hg intrusion results of the DIP paper might indicate its better ability to set ink than the virgin papers. This conclusion is parallel with the results in the literature /80/. But, this can not be seen in Table 11. The absolute change in set-off of DIP news 1 (2A) is not different among the other samples (exception sample 5A); however, the relative change is bigger due to the lower absolute set-off level. Instead, sample 5A shows very low ink setting speed, and the two-sidedness is considerable. A similar difference can be seen in the printing condition 1 and 3. No explanation for that can be found from the paper properties measured.

Table 11. Printing condition 1 and 3. Change of set-off during the delay time period from 2.5-60 s or 0-60 s, the ink amount levels are 2.0 and 1.5 g/m^2. Paper 2A is DIP news, 5A is the virgin paper.

Sample	Printing conditions 1		Printing conditions 3	
	Delta set-off 2.5-60 s	**Delta set-off 2.5-60 s**	**Delta set-off 0-60 s**	**Delta set-off 0-60 s**
	1,5 g/m^2	**2.0 g/m^2**	**1,5 g/m^2**	**2.0 g/m^2**
1A	0,12	0,14	0,23	0,26
1B	0,13	0,16		
2A DIP	0,14	0,15	0,21	0,25
2B DIP	0,14	0,16		
3A	0,13	0,14	0,25	0,26
3B	0,14	0,15		
4A	0,15	0,15	0,26	0,28
4B	0,12	0,17		
5A	**0,09**	**0,08**	**0,17**	**0,18**
5B	0,16	0,18		

Ink requirement

Many of the paper properties affect ink requirement, and the ink requirement has an effect on set-off. The measured values are presented in Appendix 4(1-4) and the averages are used in the calculation of the linear correlation. The values of both sides of papers were used and the significant correlations of ink requirement at print density 1.0 D with compressibility are seen in this order of the magnitude:

positive: ash 550 ºC and 925 ºC, roughness PPS S10, EMCO S, PPS S20, opacity
negative: compressibility (PPS S5/10), Y-value, L*, and brightness (ISO).

DIP news, sample 2, dominates the correlation. It has lowest compressibility, relatively low brightness and highest roughness, which require clearly more ink for a given print density. Generally, the correlation at 0.9 D is on the lower level except the correlation of the values indicating brightness.

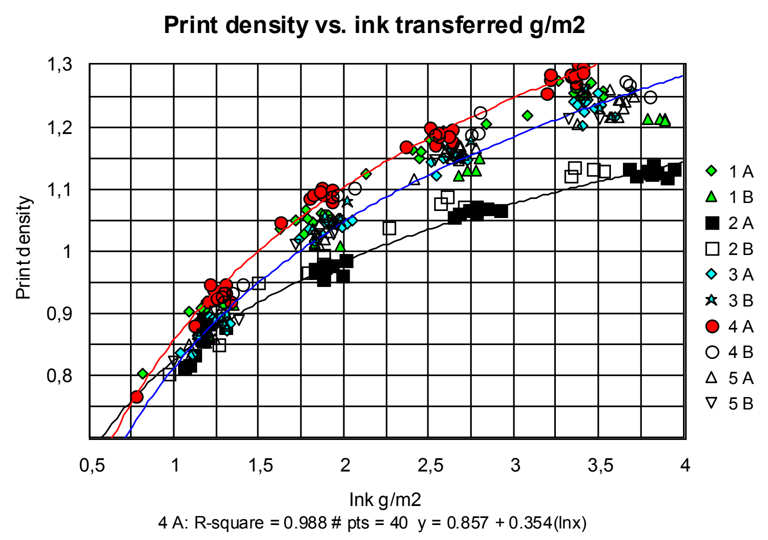
A summary of the multi regression analyses /118/ is presented in Table 12. The analysis was progressed by monitoring the insignificant variables in the given stepwise model and removing them from the initial variable table, and then repeating the analysis as many times as all variables and the intercept became significant. An interesting point is that the stepwise analysis chose Bendtsen roughness (clamping pressure 98 kPa) instead of PPS S10. Bendtsen roughness does not correlate significantly with ink requirement, and it does not cross-correlate significantly with PPS S5/10 compressibility (Appendix 6(2-5). Instead, PPS S10 correlates significantly with ink requirement. However, PPS S10 gives the R-square for the regression model only 1.5% unit lower than Bendtsen.

Table 12. Summary of stepwise regression; depended variable: average value of ink requirement at D = 1.0.

Variables	**Step**	**Multiple R**	**Multiple R-square**	**R-square change**	**F to enter/ remove**	**p-level**	**Coefficient B**	**Beta**
Intercept						0,0001	3,99	
Compr. PPS5/10	1	0,837	0,700	0,700	18,659	0,0012	-2,02	0,144
Bendtsen roughness	2	0,928	0,862	0,162	8,215	0,0241	0,0027	0,144

Whole model: $R = 0{,}928$; $R^2 = 0{,}862$; Adjusted $R^2 = 0{,}822$; Std. error of estimate = 0,083;
$F(2,7) = 21{,}85$; $p < 0{,}001$

The two variables of the final model explain 86% of the variation in the ink requirement values and PPS S5/10 compressibility is the main determining variable with the 70% R square. The remaining 14% can be related to the paper samples and the test method, specifically to the variation of the ink transfer in the printing nip. The standard deviation of the interpolated values varies 0.016-0.083 and it can explain a great deal of the remaining variation (Appendix 6(1)). This can also be seen from Figure 51, where print density is a function of the ink amount transferred to paper.



	ln(Ink 4A)	Intercept	Standard error of the regression model
Co-efficient	0,354	0,857	
Standard error	0,00621	0,00516	
p	2,1E-38	5,47E-56	0,0154

Figure 51. Samples 1-5 on both sides A and B were printed with a Prüfbau laboratory printing machine, four inking levels, measured both 2.5 s and 60 s printing. The regression model and the error estimates are for the sample 4 A.

Print through and strike through

No significant correlations are seen between set-off and print through or strike through in this test series (Appendix 6(2-5).

Discussion of the set-off vs. paper and printing properties

Better surface compressibility decreases ink requirement. Its effect on set-off is opposite. Contrary to that, higher roughness increases the ink requirement but decreases set-off. In addition, the differences in brightness add a parameter to the set-off analysis.

The paper properties commonly correlate better with the set-off values interpolated at the constant amount of ink transferred than with the set-off values interpolated at the constant print density. The paper properties bulk and ash values correlate significantly with both set-off values at the constant print density and ink amount transferred. The other properties correlate almost exclusively with the values interpolated at the constant amount of ink transferred. Correlation coefficients are quite high between printing results and ash content due to filler content of DIP based newsprint. In many cases, DIP news 1 performed exceptionally from the others. Because only 5 or 10 cases were correlated, the results can only provide a trend.

6.2.7 Set-off vs. print density or vs. ink amount

As it has already been seen, set-off performs differently if it has been presented as the function of print density or of the ink amount transferred onto paper. One reason is the logarithmic relation between the ink amount and print density. However, also the differences of the paper properties cause changes to set-off.

Because in this test series, the DIP news 1 needed more ink than the virgin papers to reach the target print density, the relationship of set-off vs. print density after 2.5 s delay (Figure 52) gives a different picture than set-off vs. ink transferred. (Compare almost linear relation in Figure 50.) At the normal print density levels, 0.9-1.0 D DIP news 1 had the lowest set-off. If higher print densities were required, the benefit of DIP paper would be lost. Also, the same picture can be seen after 60 s delay (Figure 53). The MFS grades with higher brightness are on a lower level of set-off. Especially, the brightest MFS 2 (A4) relates closely to the DIP news 1.

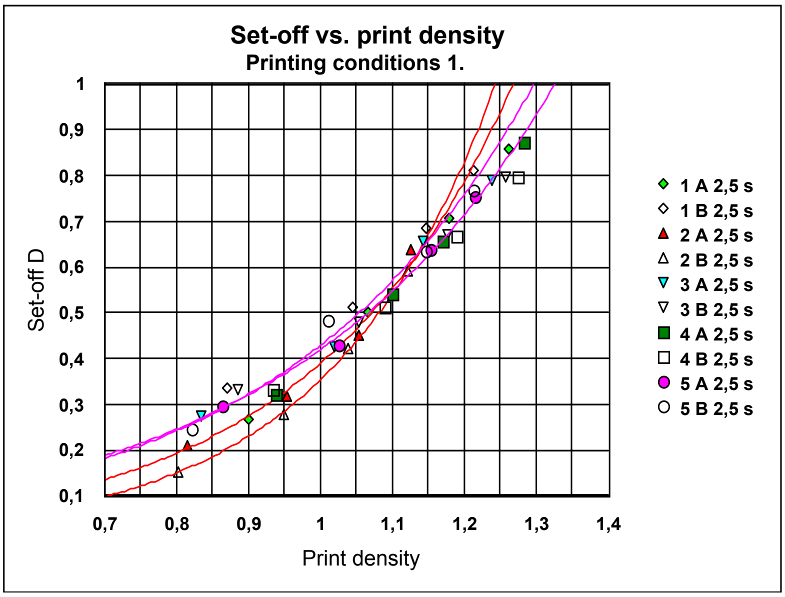


Figure 52. Set-off 2.5 vs. print density, the' own' paper as the counter paper, all papers, sides A and B. DIP paper is sample 2.

Set-off on the coated counter paper gives a similar picture to that on the ‘own paper’ however the set-off level is higher (Figure 54).

DIP news 1 becomes closer to the virgin news types when set-off was defined at the constant print density. It can be explained by its higher ink requirement that is caused by low compressibility and high roughness. These are contradictory properties for set-off, but their total effect on set-off is decreasing.

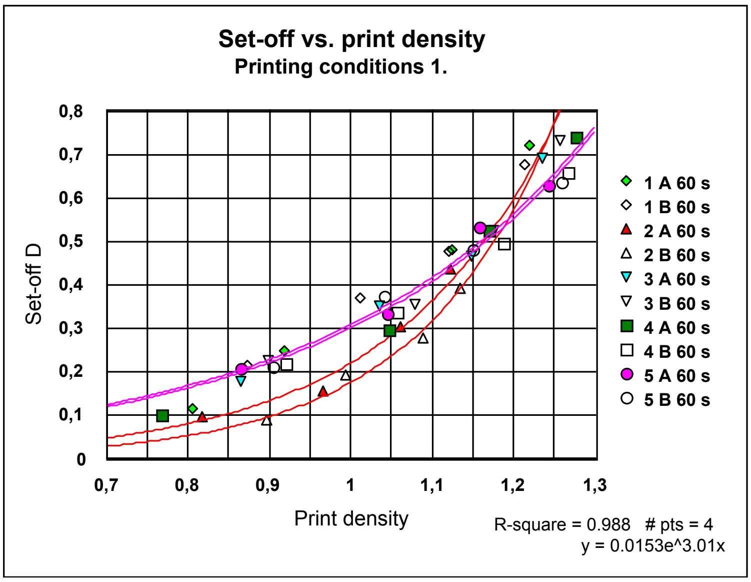


Figure 53. Set-off 60 s vs. print density, the' own' paper as the counter paper all papers, sides A and B. Regression model is for 5 A 60 s. DIP paper is sample 2.

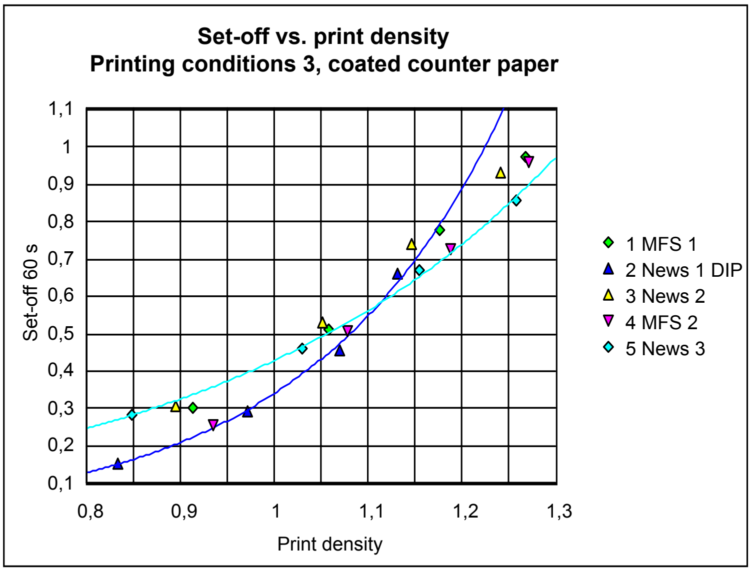


Figure 54. Set-off 60 s vs. print density, the coated grade as the counter paper, all papers, sides A and B.

6.2.8 Effect of the set-off pressure on set-off

In the Taguchi analysis, an important parameter for set-off was the pressure in the set-off situation. The noticeably higher pressure increased set-off. The effect might be higher with more compressible virgin papers but no notable difference can be seen (Figure 55 on the left). The relative effect of the set-off pressure on set-off follows the same linear line with both 2.5 s and 60 s delay time. In all the cases, when the pressure is increased, the contact area between the ink layer on the printed paper and the surface of the counter paper increases roughly in the same proportion. Set-off increases by about 30% on average from 10 to 20 kN pressure in the set-off nip.

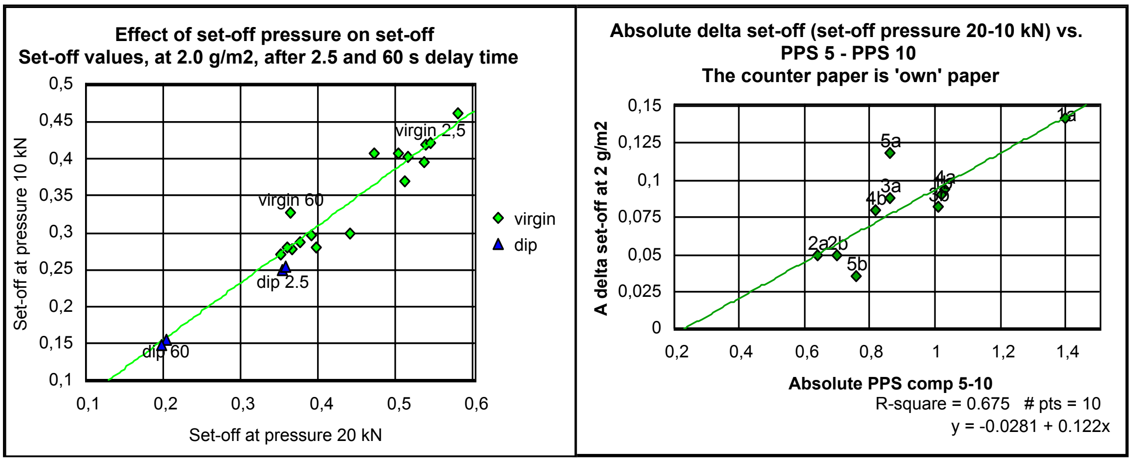


Figure 55. Effect of set-off pressure on set-off. Set-off is measured at a constant ink amount 2.0 g/m², paper sides A and B.

On the left: The effect of set-off pressure on set-off; printing condition 1 vs. printing conditions 2. Set-off values at the constant ink amount 2.0 g/m², and after 2.5 and 60 s delay time, paper sides A and B.

On the right: The correlation delta set-off vs. compressibility as PPS S5 minus PPS S10 is shown in the picture, delay time is 60 s.

In appendix 6(6-8), the calculated PPS compressibility values are given as well as their correlation coefficients with the set-off values and the calculated delta set-off values. Also, values of 'Printing pressure requirement' created by Bristow /122/ are correlated. Definitions of the parameters discussed below are given in the following list:

- Bristow's 'Printing pressure requirement' is PPS clamping pressure interpolated to a reasonably constant PPS roughness (in this study for newsprint, 4.0 µm is used) for different paper samples.
- Absolute delta set-off is the difference of set-off with the set-off pressures 20 and 10 kN/m, i.e. set-off 20-10 (about 4 and 2 MPa respectively with a 5 mm wide nip).
- Absolute PPS compressibility is the difference between PPS S5 and PPS S10, i.e. PPS 5-10.
- Relative delta set-off is (set-off 20 kN)/(set-off 10 kN).
- Relative PPS compressibility is (PPS S5)/(PPS S10) i.e. PPS 5/10.

PPS 5-10 has the best correlation with the absolute delta set-off (Figure 55 on the right). The result shows that surface compressibility is important not only for the direct set-off but also, the compressibility measured with the different set-off pressures 10 and 20 kN gives a similar indication to the absolute PPS compressibility. Bristow's 'Printing pressure requirement' did not correlate significantly with either the absolute or relative delta set-off. Instead, it cross-correlates with PPS values and with PPS S10 the correlation coefficient 0.986 is the highest. Bristow's 'Printing pressure requirement' has also significant correlations with original set-off and it is a little better than PPS S10 has; i.e. Bristow's 'Printing pressure requirement' predicted set-off a little better than PPS S10.

6.2.9 The importance of the counter paper for set-off

In practice, the facing paper can be different from the printed one especially if a hybrid printing method is used. That is, a part of the newspaper is printed with CSWO method and another part by heatset offset, when glossy coated paper grades can also be mixed into newspaper. Another case is inserting coated or SC paper advertisements printed separately between fresh newspaper pages.

Two different types of counter paper were used in these set-off printing tests: 1) the ‘own paper’ or the same paper as printed and 2) a smooth, highly coated fine paper. Set-off values are about 30% higher on the coated paper than those of the ‘own paper’ (Figure 56). The relation in this case is slightly exponential with x power 0.95, because the line turns towards the origin at low set-off levels.

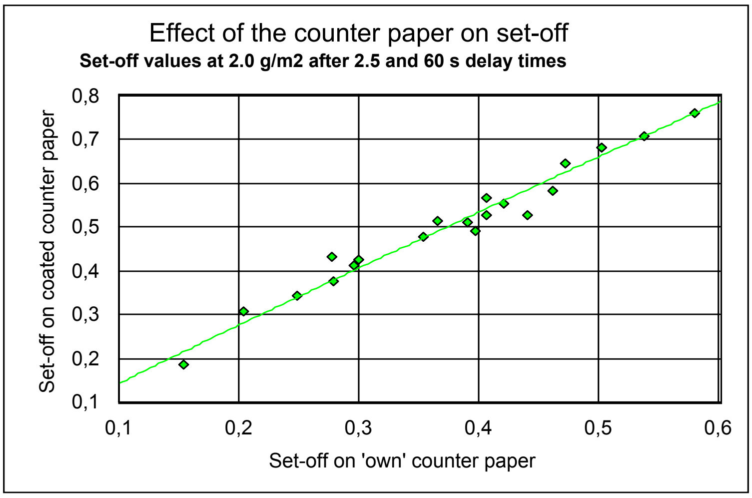


Figure 56. Effect of the counter paper on set-off. Set-off values at a constant ink amount 2.0 g/m^2 after 2.5 and 60 s delay time. Printing condition 1-4, paper side A.

The rough surface of the ‘own paper’ can not accept ink from the printed sheet as easily as the smooth, coated paper does. In production scale printing, commonly the facing paper is the same paper as the printed or ‘own paper’. That is why it is well justified to use ‘own paper’ in laboratory testing as well. On the other hand, the smooth counter paper can give more information about the set-off phenomenon. This is discussed in more detail in chapter 6.5.3. The smoother surface gives more contact with the ink printed on newsprint. Also, when one uses papers made with a sheet mould, it is practical to use another paper grade as the counter paper, because it is not necessary to produce so many sheets.

6.2.10 Summary of the results of Test series 1

Five mill papers: 2 virgin fibre MFS papers and 3 standard newsprint types (DIP and virgin fibre papers) were printed with Prüfbau laboratory printing press for investigating the set-off phenomenon under different printing conditions.

When the DIP news 1 (A2) and the virgin news 3 (A5) were compared all the parameters investigated by the Taguchi analysis (paper, ink amount, print density, counter paper, set-off pressure, and delay time) affected set-off significantly. Strike through and set-off showed no disagreement with each other, because DIP paper showed both lower set-off and strike through than the virgin paper. The biggest difference from the set-off point of view was seen in DIP news 1 with 100% DIP (A2) and news 3 (A5) with 100% virgin pulp. The ink amount transferred onto paper was about 40% higher in the DIP point than in the MFS point; however, DIP news 1 had the lowest set-off at the normal print density levels. The MFS points had the benefit of their higher brightness because less ink was needed for the target print density. Thus, the brightest MFS 2 had almost the same set-off as the DIP news 1 at the constant print density 1.0. The higher ink requirement of the DIP point was caused by its lower surface compressibility and brightness and its higher roughness. Mercury intrusion and BET specific surface analysis indicated a better ability to set ink for the DIP paper that was also seen in the results, as the greater relative change in set-off during 60 s delay time.

Set-off increased by about 30% when the set-off pressure was changed from 10 to 20 kN/m. Also, the same magnitude of increase in set-off was seen when a coated counter paper was used instead of the same paper as printed.

6.2.11 Conclusions

The printing parameters: target print density or the ink amount transferred on paper, delay time before the set-off situation, set-off pressure, and newsprint type either DIP or virgin are important for the final set-off result. Higher specific surface area and a higher amount of fine pores < 1 µm of paper seem to give an indication, which is positive for good ink setting. The other paper properties important for decreasing set-off are especially high roughness and brightness and low surface compressibility (decrease of roughness under pressure). The paper properties are the same as Karttunen and Lindqvist mentioned earlier /6/.

6.3 Simulating DIP furnish for the set-off study - Test series 2

6.3.1 Target

The target for Test series 2 is to find the reasons for the superiority of the DIP paper from the set-off point of view. This target was approached by simulating the components of DIP, and by finding the properties of the sheets made of the simulated DIP, which would fit in with the properties of the sheets made of deinked pulps.

6.3.2 Test methods and furnishes

Two deinked pulps from different mills have been compared with the simulated DIP pulps made of chemical and mechanical pulps. The deinking process has not been simulated. Thus, only virgin pulps have been used in the simulated furnishes. Chemically treated mechanical pulp, CTMP, has also been tested. Deinked pulps contain fillers, which mainly come from magazine waste papers, and for this reason, filler loadings have been used as well.

A sheet mould paper series was made from18 different furnishes using a sheet robot machine (Thwing-Albert Europa, Computerized Sheet former). Sheets were calendered at three levels of calender loads by a laboratory sheet calender (Oy Gradek Ab). The calender was one-nip calender with a paper roll / steel roll nip. The sheets were led through the nip turning a sheet after every run. Papers were printed with a Prüfbau laboratory printing machine at three inking levels with the short and long delay time of 2.5 and 60 s for set-off. Prüfbau test printing conditions are presented in Appendix 2(2). The set-off counter paper was a coated fine paper. The parameters and furnishes for Test series 2 are in Table 13.

Table 13. Parameters for Test series 2.

Calendering	**Prüfbau laboratory printing**	
1+1 nips	3 inking levels	
3+3 nips	2,5 s delay time for set-off	
5+5 nips	60 s delay time for set-off	
Sheet robot furnishes:		
100 TMP 1*)	100 DIP 1*)	5 Filler 1 with TMP 1
87.5 TMP 1 + 12.5 chemical pulp	75 DIP 1 + 25 TMP 1	12 Filler 1 with TMP 1
75 TMP 1 + 25 chemical pulp	50 DIP 1 + 50 TMP 1	20 Filler 1 with TMP 1
50 TMP 1 + 50 chemical pulp	100 DIP 2*)	5 Filler 2 with TMP 1
100 CTMP	50 DIP 2 + 50 TMP 1	12 Filler 2 with TMP 1
50 CTMP + 50 DIP 1	75 DIP 2 + 25 TMP 1	20 Filler 2 with TMP 1

*) Reference pulps

6.3.3 Pulp analysis and fillers

TMP, two deinked pulps, one CTMP and a reinforced chemical pulp from different mills were used. The pulps had been refined, ready for paper in the mills. The pulp analyses are presented in Table 14. Two filler types, a spherical (Filler 1, carbonate) and a platy (Filler 2, clay) type were used.

Table 14. Analyses of the pulps for Test series 2.

Pulp	**CSF**	**Chemical pulp content**	**Bauer-McNett**					**Mini-Sommerville shives**	**FS-200 average fibre length**
			+16	**+28**	**+48**	**+200**	**-200**		
	g	%	%	%	%	%	%	%	mm
TMP 1	91	0	29,0	8,9	15,8	8,2	38,1	0,266	1,75
Chemical pulp	541	100	69,7	6,0	10,8	4,8	8,7	0,032	2,23
DIP 1	115	35	20,6	8,2	21,9	12,3	37,0	0,044	1,28
DIP 2	143	38	20,9	7,7	19,9	14,4	37,1	0,043	1,21
CTMP	114	0	21,8	11,1	25,8	12,7	28,6	0,019	1,39

6.3.4 Sheet testing and printing results

The normal laboratory analyses of sheets were carried out. The Prüfbau printing results are found in Appendix 7(1-2) and the paper properties measured in Appendix 8(1-2). Filler contents are presented as ash content made at 925 °C and the carbonate content at 575 °C. The content of carbonate in DIP samples was low ca. 1%. The set-off measurements have been interpolated at a constant (2 g/m^2) amount of ink transferred (Appendix 8(1-2)) instead of a constant print density to neglect the influence of the range of brightness (53.4-66.5%) on the set-off results. Because the three calendering levels dominated the correlations, the set-off results have been interpolated or extrapolated also at a constant (3.5 µm) roughness PPS S10. Linear correlations have been made to establish the most important parameters from the set-off point of view (Appendix 8(3)).

6.3.5 Effect of calendering on sheets

Bulk is a measure of how a sheet has reacted during calendering. The three calendering stages have created bulk over a range of 1.24-1.93 cm^3/g for the test points (Figure 57). PPS S10 roughness correlates significantly (R^2 = 0,616) with bulk. The lightest calendering (1+1 nips) gives the highest roughness and bulk. This calendering stage clearly differs from the other. The practical range of bulk 1.5-1.7 and roughness 3-4.5 has been comfortably achieved with all the test points except 100% DIP 2, which was overly calendered.

From the results, it can be seen that the test points of TMP and filler loading locate on the right edge of the PPS-bulk band in Figure 57. While, the points made of 100% deinked pulps, CTMP, or the mixture of chemical pulp/TMP 50/50, locate on the left. The left side sheets have lower bulk and higher roughness. The sheets have lost their thickness easier than the right side sheets.

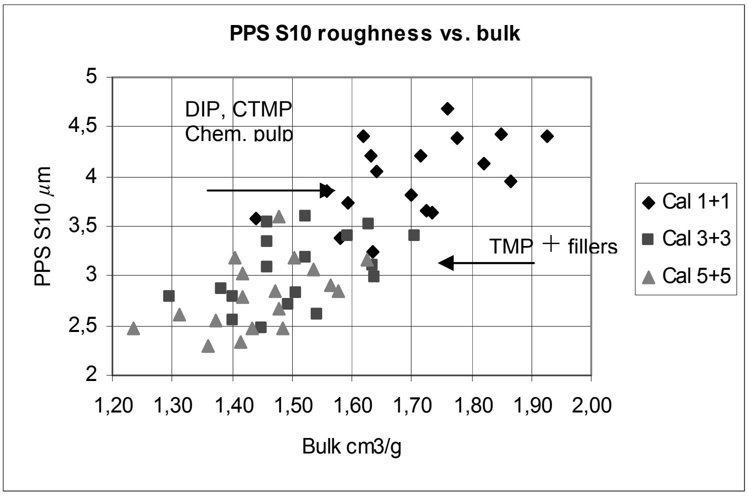


Figure 57. All 18 test points calendered through the calender nip 1+1, 3+3, and 5+5 times.

6.3.6 Simulation of deinked pulp

Simulation of DIP news was performed by adding soft wood chemical pulp, and fillers to a thermo mechanical pulp made for newsprint. Also, different amounts of the two deinked pulps were mixed with TMP to create a reference line for the simulation. The short (2.5 s) and the long (60 s) delay times were taken into account.

Figure 58 illustrates the set-off results interpolated at a constant (2 g/m^2) ink amount and a constant (3.5 µm) PPS S10 roughness. In comparison with 100% TMP, both deinked pulps decrease set-off clearly, especially with the higher fractions. DIP 2 has a greater effect than DIP 1. Also, chemical pulp decreases set-off reaching almost the level same as 100% DIP 1. The trend is the same for 2.5 and 60 s delay times. On the other hand, the relative difference in set-off of DIP 2 is higher with 60 s delay time than with 2.5 s, which might be due to the better ink setting of that pulp. CTMP pulp was tested alone, and 50/50 with DIP 1. It clearly has a lower set-off than 100% TMP. The mixed point CTMP with DIP 1 locates on the same point as 100% CTMP, but the level is a little higher than 100% DIP 1.

The filler loading to the virgin TMP also gives benefits from the set-off point of view, but not clearly for the short delay set-off (Figure 58 on the right). For ink setting, or set-off after the 60 s delay time, both fillers seem to give similar results, and the trends are almost linear. The effect is surprisingly great with the relatively high approximately 20% loading. The lower set-off value of the point 2.5 s delay of Filler 1 might be due to the spherical shape of that filler.

Conclusions: Combining the effects of chemical pulp and filler loading on decreasing set-off, the same result as the best deinked pulp DIP 1 alone has almost been reached, although the results of chemical pulp and filler loading would not be completely summable. However in fact, the simulation has been successful. On the other hand, the result gives only a technical explanation for the set-off differences between deinked pulp and virgin TMP; not any economical suggestion.

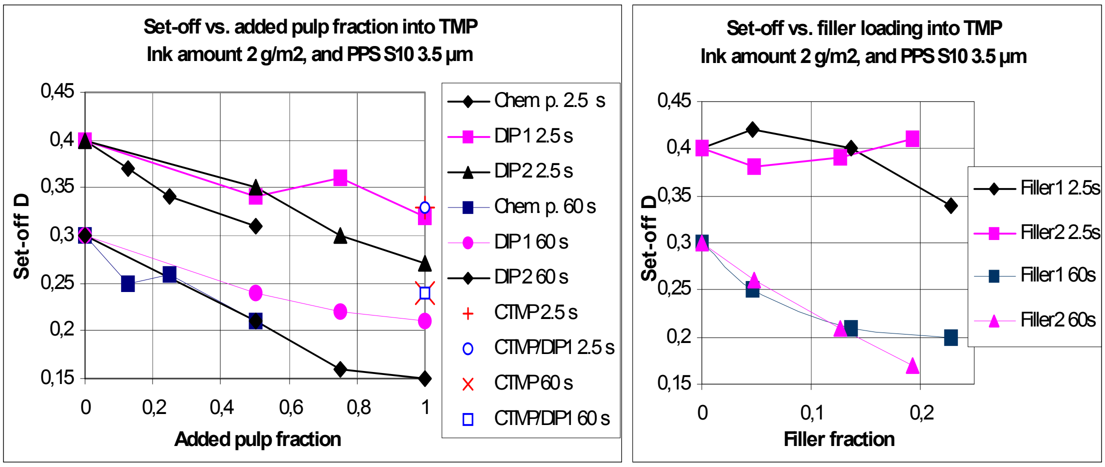


Figure 58. Simulation of DIP news adding deinked pulps, chemical pulp, and filler to TMP made for newsprint.

Bulk and compressibility of the simulated sheets vs. DIP sheets
Bulk and compressibility are interpolated or extrapolated at the constant PPS S10 roughness 3.5 µm for Figure 59 and Figure 60, in the same way as in Figure 58.

Bulk at a constant roughness corresponds to the performance of a furnish in calendering. In Figure 59, it can be noted that DIP points, 50% chemical pulp, and CTMP point have reached approximately the same level of bulk at PPS S10 roughness 3.5 µm. This means that the effect of calendering on the sheets is comparable. The fillers have a lesser effect on bulk in calendering than those pulps (Figures 59 on the right).

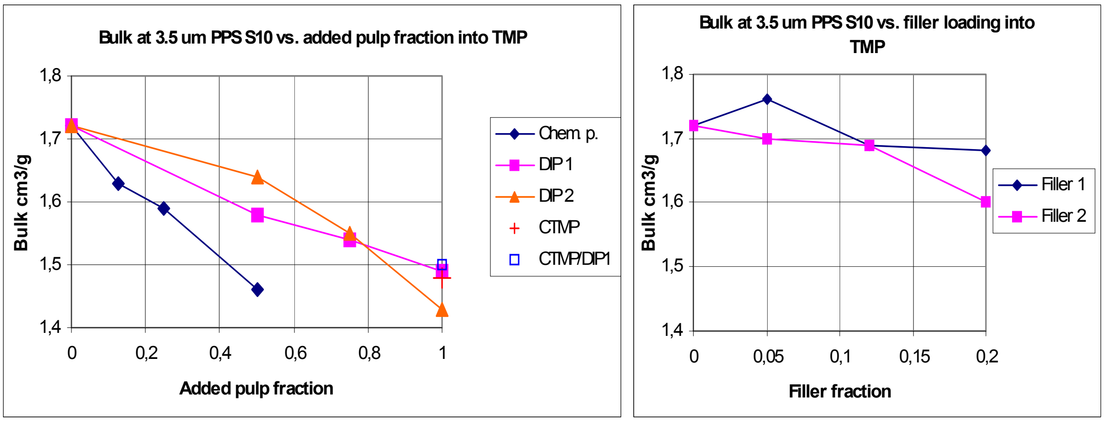


Figure 59. Decreasing of bulk of sheets at 3.5 µm PPS S10 by adding deinked pulps, chemical pulp and fillers to TMP.

Compressibility of the sheet surfaces is illustrated in Figure 60 in the same way as bulk earlier. The relative compressibility is presented in Figure 60, but also 'delta PPS' (PPS S5 minus PPS S10) gave a similar picture. As expected, chemical pulp decreased the compressibility of TMP clearly, even to a level lower than in the 100% DIP samples. The 100% CTMP point is still on a lower level. Also, a slight positive trend of compressibility with increasing filler-% is clear (Figure 60 on the right).

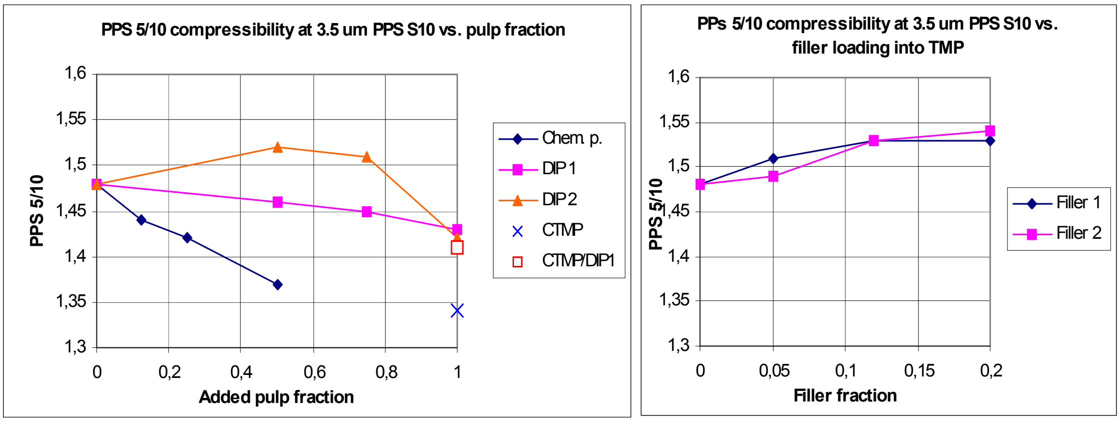


Figure 60. Compressibility of the sheets at 3.5 μm PPS S10 vs. the fraction of deinked pulps, chemical pulp and fillers added to TMP.

Conclusion: Obviously, the low compressibility decreases set-off of the chemical pulp and CTMP samples. Also the DIP points have low set-off and compressibility. DIP 2 performs differently in 50 and 75% loadings. In Figure 58, it was visible that Filler 2 does not decrease 2.5 s set-off, but it decreases 60 s set-off. Although compressibility of the sheets does not explain the results, ink setting can.

6.3.7 Discussion of the important paper properties for set-off

Linear correlations

The set-off values have been interpolated at the ink amount 2 g/m^2 transferred to paper. Correlation coefficients between the paper properties and the interpolated set-off values are presented in Appendix 8(3). The significant correlations of set-off can be seen in Table 15. Bendtsen air permeability and Cobb-Unger oil absorption did not correlate significantly with set-off, either at 2.5 s or 60 s delay time. Because of the interpolation of set-off to the constant ink amount transferred, brightness and light absorption do not correlate with set-off.

Table 15. The significant correlation coefficients between set-off and paper properties of Test series 2.

Calendering	**1+1 nips**		**3+3 nips**		**5+5 nips**	
	Set-off 2.5 s	**Set-off 60 s**	**Set-off 2.5 s**	**Set-off 60 s**	**Set-off 2.5 s**	**Set-off 60 s**
Grammage						-0,470
Bulk		0,849		0,700		0,460
Light scattering	0,600		0,723		0,790	
Bendtsen roughness		0,818		0,538		
PPS S5		0,557			-0,460	
PPS S10			-0,643		-0,630	
Compressibility PPS 5/10	0,728		0,900	0,492	0,830	0,720
Delta PPS 5-10		0,658	0,541	0,790		0,580
Gloss		-0,732		-0,618		

Correlations are significant if $|r| \geq 0.47$; $p < 0.05$.

Compressibility, both PPS 5/10 and delta PPS 5-10 have the best correlations with set-off values among all the paper properties measured, although it could be possible to draw an opposite conclusion from the results in Figure 60, when the set-off values have been interpolated at a constant roughness. An explanation is that those furnishes performed differently during calendering.

Grammage was not a variable and it does not cross-correlate significantly with the other paper properties measured. It has one exceptional correlation coefficient with set-off in the highest calendering stage, which only seems to be a coincidence. Light scattering cross-correlates well with roughness and compressibility, which can explain the correlation with set-off of the short delay. Bulk correlates with longer delay set-off especially in lighter calendering stages. Bulk has good cross-correlation with roughness and also with compressibility, but only with the compressibility measured as the roughness difference 'delta PPS 5-10'. The positive trend with 60 s set-off of Bendtsen roughness and PPS S5 can be connected with fillers, which made the sheets smoother and improved ink setting. The negative trend of PPS S10 roughness with short delay set-off is due to a rougher surface decreasing set-off and only a little setting of ink taking place.

Set-off vs. bulk

Considering bulk with set-off, the weakest calendering (1+1 nips) forms clear cluster of its own but the others (3+3 and 5+5 nips) overlapped with each other (Figure 61). The long delay set-off 60 s gives more clear clusters (coloured ovals in Figure 61) than the short delay set-off 2.5 s. In particular, some of the filler points have compressed this cluster due to the decreased set-off caused by ink setting.

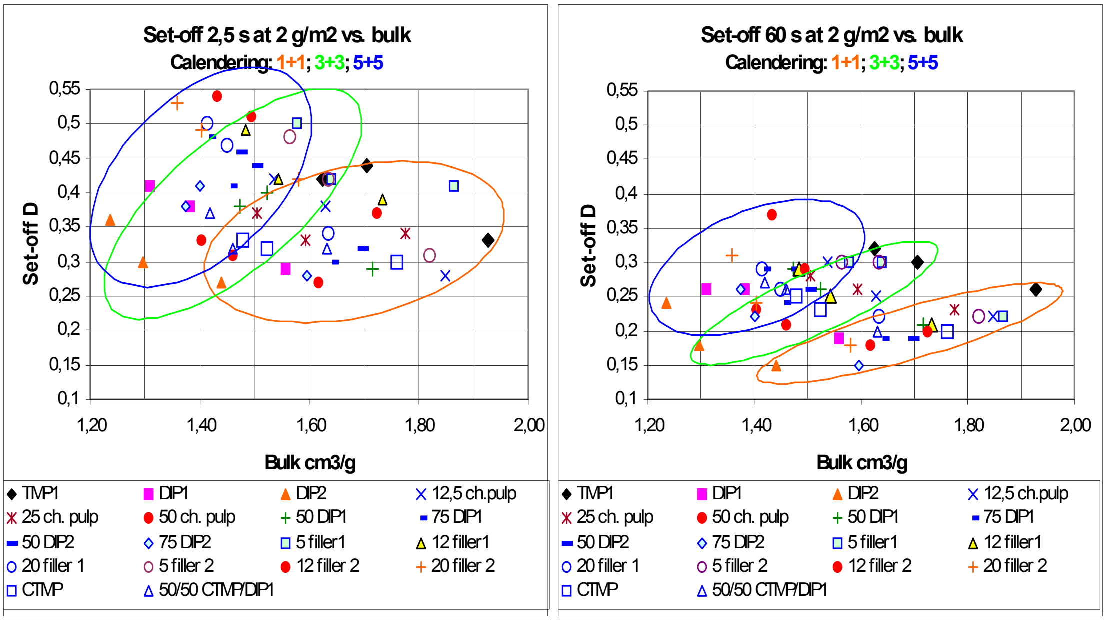


Figure 61. Calendering clusters formed by different pulps (ch.pulp is chemical pulp). Set-off values have been interpolated at a constant ink amount 2 g/m^2, delay time 2.5 s on the left and 60 s on the right.

Bulk assorts the furnishes inside each calendering stage. The virgin TMP 1 locates in the one end of the calendering clusters and DIP 2 in the other end. Calendering has been too severe for DIP 2 because its bulk is almost too low for newsprint. The point of 75% DIP 2 has the same low set-off value but its bulk is acceptable.

Bulk itself is not important for set-off directly, but it visualizes how much calendering is required in order to reach a certain bulk level. The lower calendering requirement gives a possibility to produce a rougher surface. Higher roughness is positive for decreasing set-off. In this test series, such a situation was created by adding chemical pulp to TMP for simulating deinked pulp. The same situation was reached with 100% CTMP.

Set-off vs. PPS S10

Increasing roughness is regarded as an important parameter for decreasing set-off. In Figure 62, all the values of 2.5 s set-off are presented as a function of PPS S10 roughness. A clear negative trend of set-off as a function of roughness can be seen. Also, most of the individual furnishes have approximately the same trend which points out that the trend comes from the calendering stages. This has also been seen from the literature studied. The pulp points are presented in the left picture and the filler points on the right.

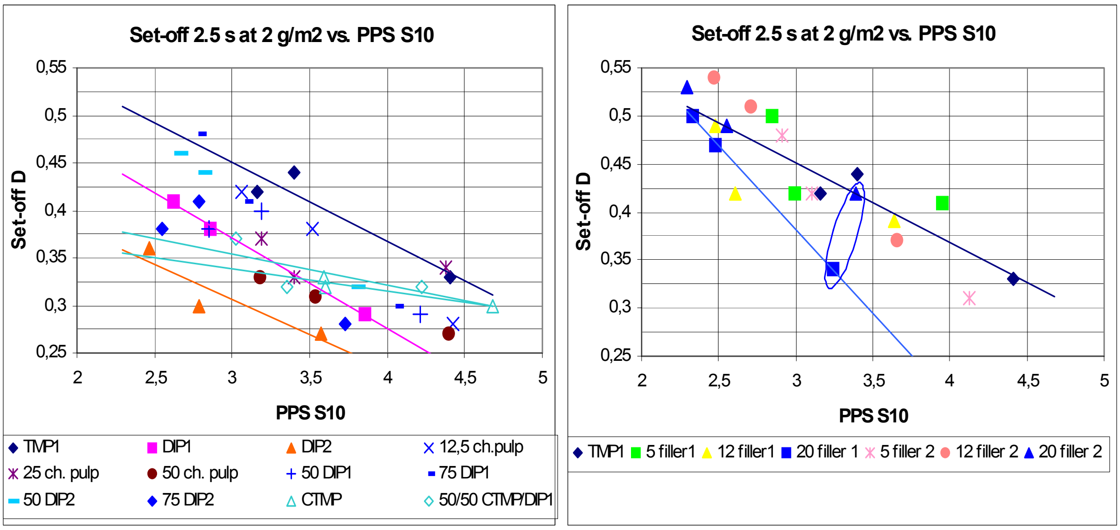


Figure 62. Roughness of the sheets made of 18 furnishes (ch.pulp is chemical pulp). Three calendering levels: 1+1, 3+3 and 5+5 nips. The blue oval (on the right) is for pointing out the test points with the highest filler loading at the calendering level 1+1 nips.

Some of the pulp points with a lower share of DIP or chemical pulp locate close to TMP points (Figure 62 on the left). The points with 100% DIP or 50% chemical pulp with TMP form a cluster of their own but the trend is the same as with TMP points. Set-off of CTMP points have a lower trend line than the others being lesser dependent on roughness.

When a relatively large amount (20%) of filler was added to TMP, bulk decreased, but also roughness of the sheets became the lowest in the cluster of the first calendering stage (oval in Figure 62). That is why; the filler loading does not decrease set-off in the short delay time 2.5 s. As it could also be seen in Figure 58 the lowest calendering point '20% of Filler 1' has clearly a lower set-off than the point '20% of Filler 2'.

Compressibility vs. set-off

If compressibility is low, then also set-off is low. All the trends in Figure 63 are statistically significant except set-off with the calendering 1+1 nips and 60 s delay time with $r^2 = 0.03$. Especially with the 2.5 s delay time, set-off is clearly dependent on compressibility. The compressibility has been measured by a static method. It is also comprehended that the dynamic compression in the set-off situation would be important.

For the set-off after 60 s delay time, compressibility and roughness of paper, and also ink setting are important. That is why the role of compressibility is not major. However, with the two harder calendering efforts it is significant.

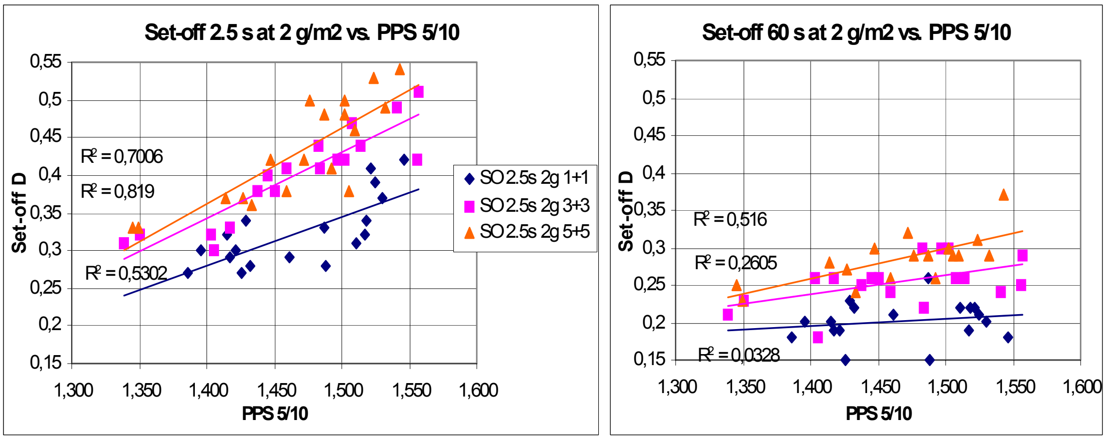


Figure 63. Set-off (SO) vs. compressibility. Set-off after the shorter delay time 2.5 s on the left and after the longer delay time on the right. R^2 are for the trend lines, the lowest position for the lowest trend line etc.

<u>Set-off vs. absorbency</u>
The paper properties which correspond with pore structure and liquid absorption i.e. air permeability and oil absorption, were not able to explain the differences in set-off of the laboratory sheets tested. However, it is obvious that a certain type of absorbency ought to be important for long delay set-off and ink setting.

6.3.8 Summary for the simulation of DIP furnishes

Simulation was prepared adding reinforced chemical pulp or fillers into virgin TMP. Also, mixtures of two DIPs and TMP, and 100% CTMP were tested. The simulation was successful, and the same low set-off values as 100% DIPs were achieved with the best simulation pulps. It was found that in calendering, pulps (DIPs, CTMP, CTMP+DIP, and TMP/chemical pulp 50/50) perform in the same way according to bulk and roughness. These pulps also have low set-off.

In this test series, the reasonable set-off levels have been 0.3 D for 2.5 s delay time and 0.2 D for the 60 s delay time. In Table 16, all the test points, which have reached one of these levels, have been displayed. TMP 1 point has been used as a reference.

<u>Mixing fillers with TMP</u>, the short delay (2.5 s) set-off was clearly lower only with a high amount (20%) of the spherical filler. The others were at the same level as the reference TMP or of a slightly lower level. With a longer delay time (60 s) all filler points gave clearly lower set-off than the reference, the highest load of filler had the lowest set-off. The lowest set-off was achieved with Filler 2 having a platy particle shape form and 20% loading.

<u>DIP vs. TMP:</u> The pulps containing DIP clearly had lower set-off than the reference pulp TMP 1, the more DIP the less set-off with both DIPs. DIP 2 had the lowest set-off. The same trend was seen with long and short delay times. The pulp DIP 2 differed from DIP 1. The pulp analysis (Table 14) shows that there are no big differences in fibre length distribution or in the average fibre length. DIP 2 had a slightly higher filler content, it contained a little more chemical pulp (38% vs. 35%), and maybe also more finer mechanical pulps coming from magazine grades. The average fibre length of the TMP pulp was clearly the longest, and it had no filler load.

Table 16. The test points which had 2.5 s set-off ≤ 0.3, or 60 s set-off ≤ 0.2 and the reference TMP 1. Set-off values have been interpolated at a constant ink amount 2 g/m^2.

Sample	**Fraction in furnish**	**Calendering**	**Set-off 2.5s 2g**	**Set-off 60s 2g**
1 DIP2	1	1+1	0,27	0,15
1 50 chemical p.	0,5	1+1	0,27	0,18
1 12,5 chemical p.	0,125	1+1	0,28	0,22
1 75 DIP2	0,75	1+1	0,28	0,15
1 DIP1	1	1+1	0,29	0,19
1 50 DIP1	0,5	1+1	0,29	0,21
1 75 DIP1	0,75	1+1	0,30	0,19
1 CTMP	1	1+1	0,30	0,20
2 DIP2	1	3+3	0,30	0,18
1 50 DIP2	0,5	1+1	0,32	0,19
1 50/50CTMP/DIP 1	0,5/0,5	1+1	0,32	0,20
1 12 Filler 2	0,12	1+1	0,37	0,20
1 20 Filler 2	0,2	1+1	0,42	0,18
1 TMP 1	**1**	**1+1**	**0,42**	**0,32**

CTMP and mixing chemical pulp with TMP: Both the chemical pulp and the CTMP decreased set-off clearly, the higher the addition the lower the set-off. The 50% level of chemical pulp gave about the same set-off level as 100% DIP 1. The same type of results were seen with long and short delay times. The 100% CTMP is close to the 100% DIP 1 pulp from the set-off point of view, and the mixture of 50/50 gave almost the same results.

6.3.9 Conclusions of set-off analysis of pulps and fillers

DIP pulps gave a clearly lower set-off than the reference pulp TMP, both at the short and long delay time. DIP pulps contain chemical pulp and filler coming mainly from magazine grades. Thus, the fillers also contain fine coating pigments and some carbonates. For the same reason, the mechanical pulp is finer on average. This test series illustrates the effect of adding chemical pulp and fillers into TMP. However, the TMP used was a normal pulp for newsprint. The chemical pulp and fillers decreased the set-off values of TMP. Obviously, fillers open the structure of the paper surface forming small pores around the particles and thus improving the setting of ink. CTMP also had the lower set-off than TMP samples. In addition CTMP had lower bulk values but a slightly higher roughness than TMP samples at all the calendering loads, and one of the lowest compressibilities PPS 5/10. The lower compressibility can explain at least part of the lower set-off values.

The methods i.e. Cobb-Unger and Bendtsen air permeability, used for measuring pore structure of the sheets could not explain the ink setting differences in Test series 2. Newsink can set by solvent (oil) separation from the ink film to the interior of paper. As discussed earlier in chapter 5.4, the ink oil components can be transferred along the micro surfaces and open sided capillaries of paper as the secondary flow and absorb into the finest capillaries with capillary forces. Only the finest capillaries (about 0.5 µm or less) of a paper surface can be filled with oils during ink setting because of the small amount of liquid available. These capillaries can be measured with mercury intrusion. However, no practical method has been found to measure the paper properties that cause the secondary flow. Cobb-Unger oil absorption and Bendtsen air permeability remain quite far from these targets.

6.4 Ink setting

6.4.1 Targets for the study of ink setting

The ink studies were made to compare the different theories of ink setting in CSWO printing and to examine the role of printing ink in the set-off phenomenon. Viscosity of ink and its oil components ought to be important to ink setting. In Test series 1, no analogical dependency between set-off and strike through was found. This item is discussed more by aid of the ink test series (chapter 6.4.5).

6.4.2 Test methods and ink properties for Test series 3

Ink setting in time_and its dependence on the ink viscosity are the main subjects for this test series. Two commercial and 5 laboratory model inks were tested with a standard virgin newsprint /46/. Viscosity values of inks were measured with a falling rod viscometer Laray. The results are in Table 17. Set-off tests were performed with a Prüfbau laboratory printing press. The delay times between printing and the set-off nip were 0.17, 2.5, 15 and 60 s. The other printing conditions were the same as in Test series 2 (chapter 6.3), however the Prüfbau laboratory printing press was adjusted between these two test series. Due to this, the print densities and the set-off values are not directly comparable.

Table 17. Ink viscosity values /46/.

Ink	Laray viscosity, Pas
363/1	2.8
363/2	2.7
363/3	2.8
363/5	2.7
363/6	3.0
363/7	2.2
Ink 1	3.9
Ink 2	15.7

6.4.3 Ink setting in time, results of Test series 3

In Figure 64, the model inks are divided into two groups giving lower or higher set-off values. The commercial inks belong to the higher set-off group. The lower set-off inks contained a high amount of oils, and the higher set-off inks contained a high proportion of hard resins. One of the low set-off inks, 363/1, had a thick oil component and it has high 'zero' (0.17 s) set-off, but the set-off value drops down to a lower level in 2.5 s.

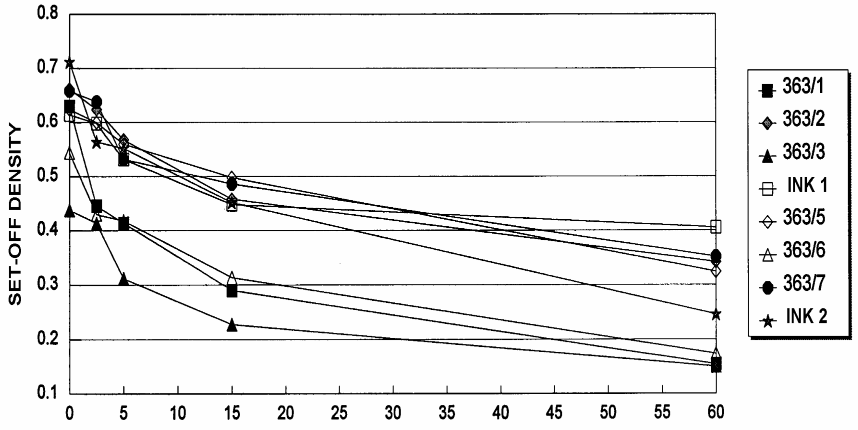


Figure 64. Set-off densities by delay time (s) at a constant print density 1.0 with eight newsinks and one paper made of 100% virgin fibre /46/.

Theoretically, (e.g. Kozeny's equation (10)) the absorption depth of a liquid in time is inversely dependent on the square root of viscosity but in this case, it could not explain the results. The test ink 363/7 with a slightly lower viscosity belonged to the higher set-off group and the ink 363/1 with the biggest change in set-off value in time had a slightly higher viscosity than the other test inks. The set-off value of the commercial ink 2 with the much higher viscosity dropped down considerably more than the commercial ink 1. The results are opposite to the idea that the whole composite of ink absorbs into capillaries of paper in CSWO printing for explaining decreasing set-off. All the inks however, gave a lower set-off values in time. Thus, the setting of the inks had to take place. Solvent separation, gives a better explanation. According to equation (10), the absorption depth of a liquid is linearly dependent also on the square root of time. The set-off values in this test series decreased more rapidly than that.

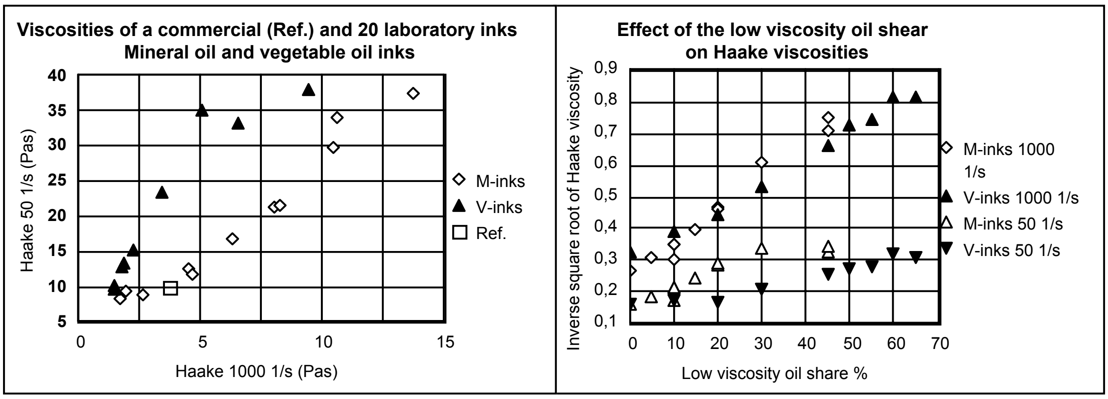
6.4.4 Viscosity of ink vs. ink setting - Test series 4

Vegetable and mineral oils in CSWO inks and their influence on ink penetration and setting, and also on the correlation between set-off and print through/strike through are the main subjects of this test series /123/.

A range of 20 black test inks was made on the laboratory scale for testing the influence of ink viscosity on print properties: ink requirement, print through and set-off. The recipes are shown in Appendix 9(1). A commercial CSWO ink was used as a reference. The paper used in the tests was constant, a standard 45 g/m^2 newsprint. The viscosity range of the inks was achieved by changing the proportion of low and high viscosity mineral or vegetable oils. Pigment content was a constant amount of carbon black and gilsonite varnish (gilsonite resin diluted into low viscosity oil) was used but the model inks did not contain the additives normally used in commercial inks.

The print properties were tested with a Prüfbau laboratory printing tester at 23 °C and 50% RH. The test procedure was the same as in Test series 2. Viscosity of the inks was measured with Haake RT 20 Rotovisco cone and plate viscometer and Laray falling rod viscometer. Haake low shear rate viscosity (50 s^{-1}) varied 8-37 Pas and the high shear rate viscosity 1000 s^{-1} 2-14 Pas at 30 ºC. The correlation between high and low shear rate viscosities is illustrated in Figure 65. The inks are shear thinning and the vegetable oil inks are more strongly shear thinning than the mineral oil inks.

The inverse square root of Haake viscosities (1000 1/s and 50 1/s shear rates) is correlated with the share of low viscosity vegetable and mineral oils in Figure 65 on the right. The correlations are almost linear but mineral oil inks cause most of the non-linearity, perhaps, because of more interaction between ink components.


Viscosities of a commercial (Ref.) and 20 laboratory inks Mineral oil and vegetable oil inks

Effect of the low viscosity oil shear on Haake viscosities

Figure 65. Low shear rate viscosity vs. high shear rate viscosity of the model inks and one commercial ink (Ref.) on the left and effect of the low viscosity oil share on low and high shear rate viscosities on the right. Results are from ref. /123/.

All the viscosity values and Prüfbau printing results were interpolated at a constant print density 1.0 D and are shown in Appendix 9(2). The linear correlation coefficients between the viscosity values and printing results are in Table 18. More details of the linear correlations are presented in Appendix 9(3-4).

Table 18. Correlation matrix viscosities and print properties of all the model inks and one commercial ink. The results are interpolated at a constant print density 1.0 D. Marked (grey background) correlations are significant at p < 0.05, N=21. /123/

	Haake 50	Haake 100	Haake 500	Haake 1000	Laray
set-off 2,5s	0,11	0,27	0,44	0,51	0,46
set-off 60s	0,12	0,32	0,52	0,59	0,56
strike through	-0,78	-0,81	-0,78	-0,79	-0,69
ink requirement	-0,91	-0,89	-0,81	-0,79	-0,70

6.4.5 Discussion of the results of Test series 4

The viscosity values of the test inks have significant correlations with the printing results. Set-off correlates only with the high shear rate viscosities; the long delay set-off better than the short one (Table 18). Ink requirement correlates better with low shear rate viscosities, when all the inks were taken into account. Strike through does not have that kind of dependency on the shear rates. When the inks are divided into groups by means of raw materials, then the oil fractions correlate with ink requirement and strike through: low viscosity mineral oil and vegetable oil fractions positively and the high viscosity oil fraction negatively (Appendix 9(3-4)).

Ink requirement

In Figure 66 on the left, ink requirement as a function of Haake low shear rate 50 1/s viscosity is illustrated. The negative correlation is high, but the production ink sample (circle) differs

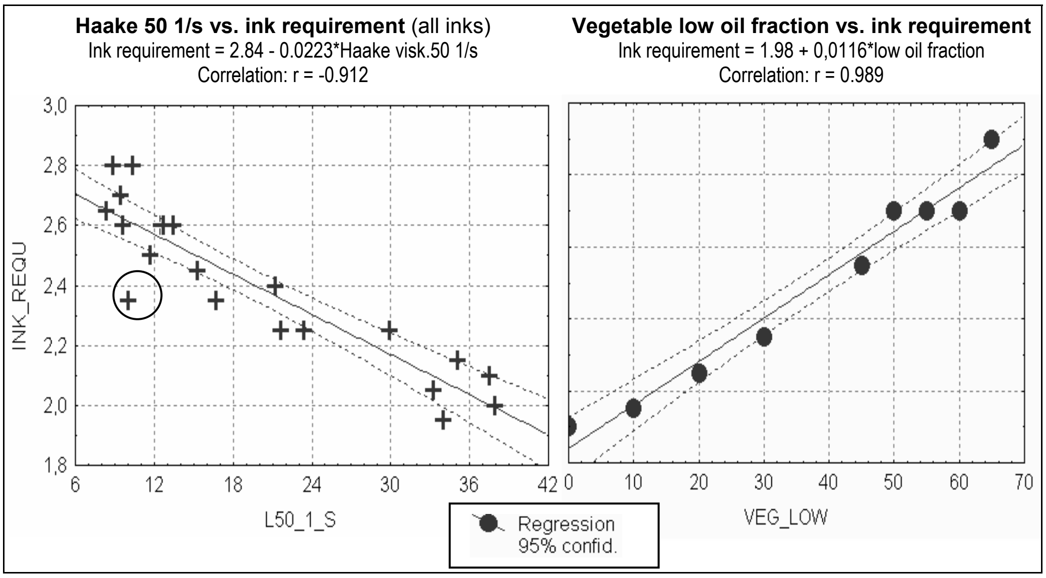


Figure 66. Ink requirement as a function of Haake low shear rate (50 1/s) viscosity Pas (left) and the fraction of low viscose vegetable oil in ink (the right, excluding sample 19) in the same scale (left).The circle in the left picture points out the commercial ink sample. Results of the ink requirement are interpolated at a constant print density 1.0 D.

mostly from the general trend line. In the right picture, the ink requirement of the vegetable oil inks is shown as a function of the fraction of low viscosity oil. The five samples with the highest ink requirements have no high viscosity oil. The sample with the lowest ink requirement contains no low viscosity oil. The mineral oil inks have a similar trend but with higher deviation; correlation coefficients are $r_M = 0.743$ and $r_V = 0.983$ (Appendix 9(3-4)).

The mineral oil model inks and the vegetable oil model inks perform differently in the viscosity measuring (Figure 65). The vegetable oil inks are more shear thinning. In Figure 67, the ink requirement is presented as the function of Haake 1000 1/s. Those two types of the model inks form different curves for ink requirement. The vegetable oil inks have almost a logarithmic relation and the mineral oil inks have practically a linear correlation. The model inks 2 and 6 have same formula for giving an indication of deviation.

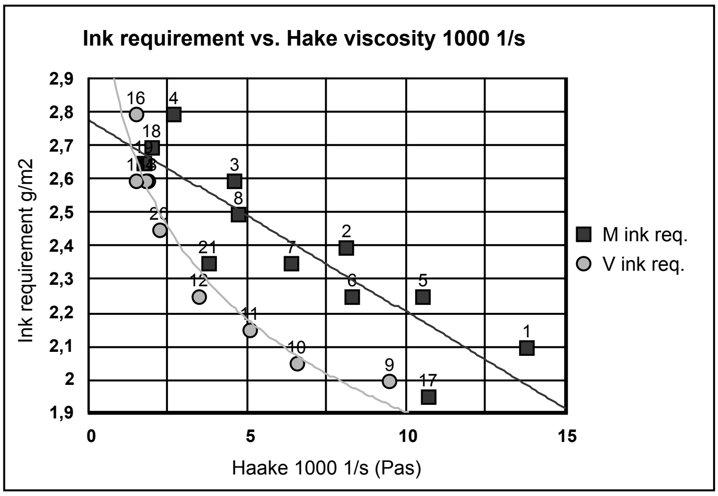


Figure 67. Ink requirement of the mineral oil inks (M) and the vegetable (V) oil inks as the function of high shear rate viscosity. Sample 21 is a commercial ink.

In the previously presented equations (8) and (10) for liquid absorption into a porous structure (Lucas-Washburn, Kozeny), the absorption is related to the inverse square root of viscosity ($\sqrt{1/\eta}$). In addition, as presented in chapter 4.2.1 equations (6) and (7), in any situations where a flow of liquid takes place between surfaces, the flow has this dependency. The ink requirement of newsprint for a given print density might function in the same way. That is because of the lateral flow to the lower pressure recesses, and to the surface voids, and also to the surface capillaries. The flow influences the ink coverage and the evenness of the ink distribution on a newsprint surface, which in turn affect the ink requirement. The ink penetration into the interior of paper increases the ink requirement.

Ink requirement is presented as a function of the inverse square root of Haake viscosity of the low and high shear rates at a constant print density 1.0 D in Figure 68. No clear differences in ink requirement could be noted between mineral oil and vegetable oil inks as the function of the low shear rate viscosities. Instead, the high shear rate viscosities divide the inks into two groups with different trend lines (Figure 68 on the right). The vegetable oil inks have a lower ink requirement at the same viscosity. The oils give different rheology for inks. The commercial ink 21 is closer to the vegetable oil inks than to the mineral oil inks. In the case of the low shear rate viscosity, the commercial ink is exceptional.

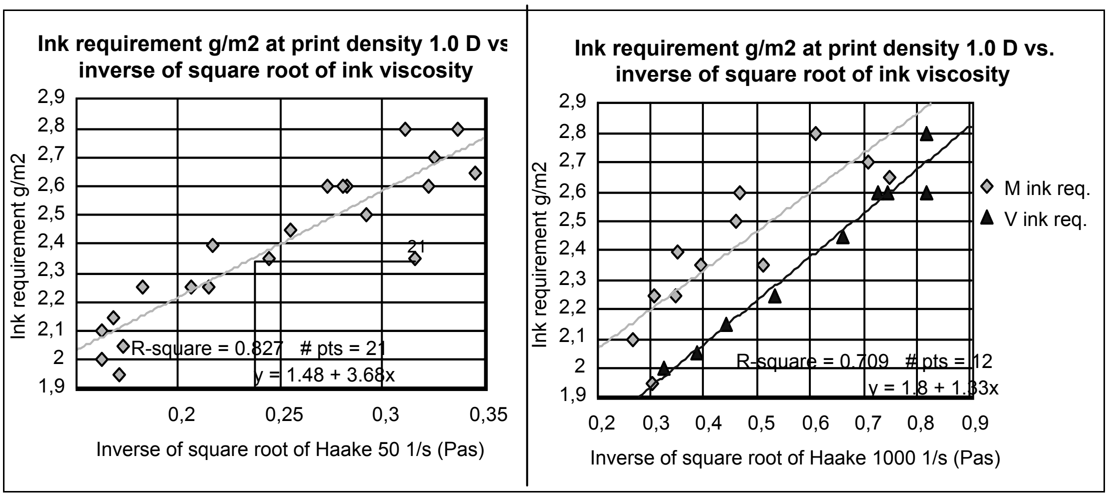


Figure 68. Ink requirement vs. low and high shear rate viscosities. The production ink is marked with number 21. R-square in the right picture is for the mineral oil inks.

It could be thought that the regression trend line of Figure 68 on the left represents the apparent low shear rate viscosities for the ink samples during ink transferring in the printing nip and in the given printing conditions. E.g., the viscosity measured for the commercial ink sample (21) is 10 Pas, but in the printing nip, the apparent viscosity is about 17 Pas calculated from Figure 68 on the left. Theoretically, the intercept (1.48) of the regression equation represents the ink requirement in g/m^2 for the ink with the infinite high viscosity. For the vegetable oil inks calculated from the high shear rate viscosity, the intercept is almost the same (1.49), however for the mineral oil inks higher (1.8). Commonly, the lower the viscosity is, the higher the ink requirement.

In fact, the significance of the direct linear correlation between the ink requirement and the low shear rate viscosity in Figure 66 is a little better than the one given in Figure 68, i.e. -0.91 and 0.83 respectively. The apparent low shear rate viscosity for the production ink (21) from the direct linear correlation is about 22 Pas, or a little higher than that of Figure 68. (The measured low sear rate viscosity is 10 Pas.)

Thinking in this way, and taking into account that the surface tension is not so important in the printing nip, in which the ink flow affecting ink requirement takes place, the apparent viscosity of the inks tested is the only factor of ink influencing the ink requirement at the given printing conditions and paper. Oittinen /12/ presented the 'effective viscosity' reading the viscosity of a non-Newtonian liquid from the tack vs. viscosity curve of Newtonian oils, which a Newtonian oil of the same tack value would have. Following this idea in Figure 68, the apparent viscosity for the CSWO production ink tested has been defined in the printing nip. The reference line is formed by model inks. The production ink sample seems to perform with a higher apparent viscosity in the printing nip than the measured one. The real shear rate for ink in a printing nip is not known. The higher the viscosity, the better the ink remains on the surface of paper, and the lower the ink requirement for the given print density. The vegetable oil model inks seem to follow more closely than the mineral oil inks, the theoretical inversion ($\sqrt{1/\eta}$) for the connection between ink requirement and viscosity.

Strike through

Strike through vs. ink requirement has a linear positive trend, and vs. viscosity a logarithmic negative trend (Figure 69).

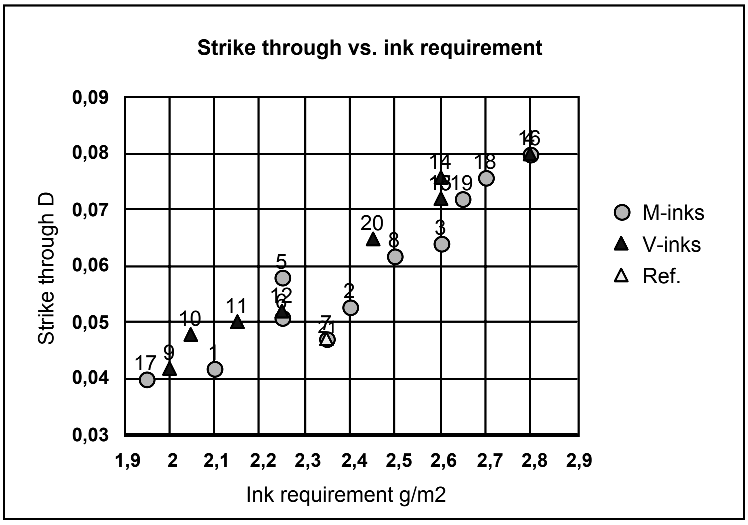


Figure 69. Strike through vs. ink requirement on the left. The production ink (Ref.) is no 21. The printing results are interpolated at a constant print density 1.0 D.

The vegetable oil inks have a little more strike through at the same ink requirement than mineral oil inks. However, on average, the strike through of the mineral oil inks is higher at the same high shear rate viscosity, but lower at the low shear rate viscosity (Figure 70). The commercial ink 21 has an exceptional low strike through in comparison with viscosity and the model inks. Using the same method as in the case of the ink requirement, for strike through the apparent viscosity could be three times higher than the measured one i.e. about 30 Pas (Figure 70).

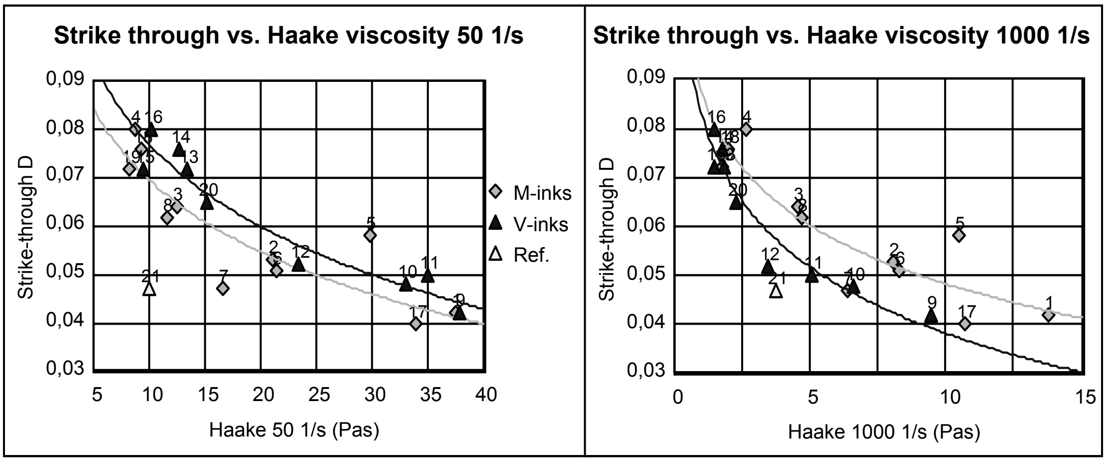


Figure 70. Strike through vs. Haake viscosity 50 1/s on the left and 1000 1/s on the right. M and V stand for mineral oil and vegetable oil respectively. Ref. is the commercial ink sample.

Strike through is illustrated also in the function of the inverse square root of viscosity (Figure 71). The vegetable oil inks again follow the theory with lesser deviation as was previously found in the case of ink requirement. The mineral oil inks have higher deviation and the commercial ink is again on an exceptional level pointing to a higher viscosity than measured.

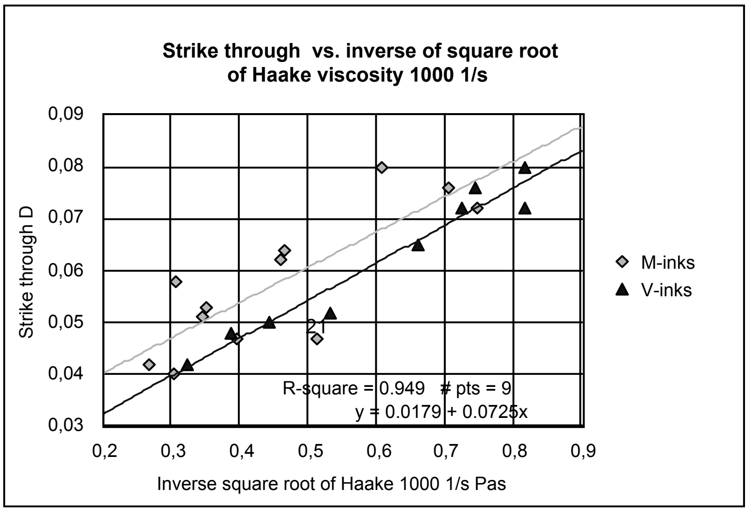


Figure 71. Strike through vs. inverse of square root of Haake high shear viscosity. Point 21 is the commercial ink sample. The linear regression analysis is for the vegetable oil inks. M and V stand for mineral oil and vegetable oil respectively.

Not only pigment penetration causes strike through, but also the mobile phase separating from the ink film and flowing into interior of paper by surface wicking. In this test series, the mobile phase fraction was not constant, because also the amount of gilsonite varnish was a variable. Despite that, the vegetable oil inks follow the theory especially well.

Set-off, ink setting

In the literature part of this study from the results of Busk's commercial inks with a constant newsprint (Figure 35, chapter 4.6), we saw that set-off was clearly dependent on ink requirement: the higher the ink requirement the higher the set-off at the print density 1.0 D. In here with the model inks, we can see the opposite trend of the vegetable oil inks or no trend at all with the mineral oil inks (Figure 72 on the left). In addition, the set-off values of the mineral oil inks are clearly on a higher level than those of the vegetable inks. The set-off of the commercial ink (21) is at the same level as the set-off of the mineral oil inks.

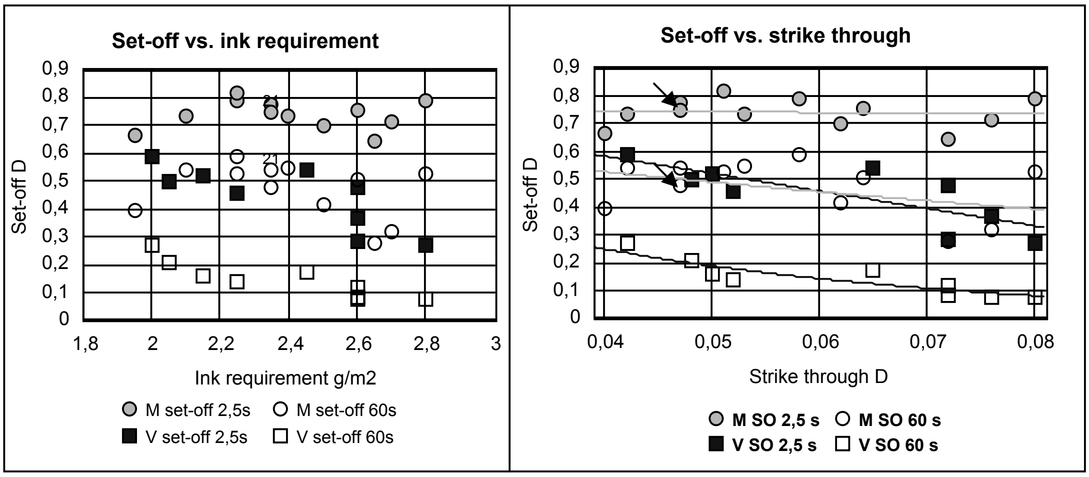


Figure 72. Set-off vs. ink requirement and set-off vs. Haake viscosity 1000 1/s , 2.5 s and 60 s delay time, the mineral oil inks (M) and vegetable oil inks (V). The production ink is marked 21 on the left and with arrows on the right. Results are interpolated at a constant print density 1.0 D.

The inverse connection between set-off measured after 2.5 s and 60 s and strike through measured 24 h after printing is found in this test series which was expected but not found previously in Test series 1 (Chapter 6.2.5). This connection is now found only with the vegetable oil inks. The contradiction of the model inks with Busk's results of ink requirement, and with the strike through results of Test series 1, can be explained by the raw materials used in the printing inks. In Test series 1, the ink was a commercial sample, and in Busk's tests the inks were also commercial samples. And, the model inks did not contain the additives normally used in commercial inks.

When the set-off values of Test series 4 are correlated with the viscosities of all the inks, the correlation is barely statistically significant and only with high shear rate viscosities, and not as high as the correlations of the viscosities with strike through and with ink requirement (Table 18). From Figure 73 on the left, it can be seen that the set-off of the mineral oil model inks and the set-off of the vegetable oil model inks perform differently regarding viscosity (Haake 1000 1/s). Haake viscosity correlates positively with set-off in some cases but viscosity alone can not explain all the deviations we can see. After 2.5 s delay time, the vegetable oil inks with the lowest viscosity (below 2.5 Pas) have the slope of the curve, which is very steep and then it continues with a lower slope. Also, set-off of two mineral oil inks with low viscosity perform similarly but only after 60 s delay time. All those model inks with low viscosity contain the highest share of low viscosity oil, and these inks do not contain high viscosity oil at all.

A rapid decreasing of set-off when the low viscosity oil share is 50 % or higher of the ink composition can be seen in Figure 73 on the right. In addition, the change of set-off during the time period between 2.5 s and 60 s is smaller than the other vegetable oil samples containing less low viscosity oil. Obviously, in the case of those inks a part of the total-ink has penetrated deeper into the paper during the printing nip dwell time having anymore no opportunity to cause set-off.

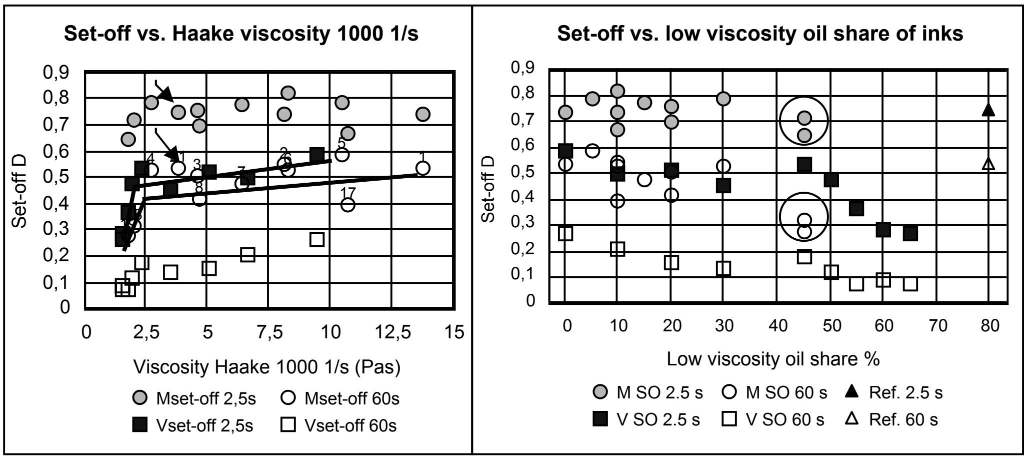


Figure 73. The effect of the low viscosity oil share on set-off (SO) 2.5 s and 60 s delay time on the left. The set-off value of the commercial ink (Ref.) is 0.75 and 0.54 for 2.5 s and 60 s respectively but the share of the low oil component of the ink composition is not known.

Set-off (SO) vs. strike through on the right. The commercial ink is marked with arrows. M and V stand for mineral oil inks and vegetable oil inks respectively. Results are interpolated at a constant print density 1.0 D.

The mineral oil inks have no clearly similar performance at the 2.5 s delay; instead, we can see the same kind of phenomenon at 60 s delay. As with the low viscosity vegetable oil inks, the two model mineral oil inks giving low set-off at 60 s delay contain no high viscosity oil at all. One contains 45 % low viscosity mineral oil and the other 20 % + 25 % mineral and vegetable low viscosity oils respectively. These two model inks (circle) have an exceptionally great reduction of set-off during the time period between 2.5 s and 60 s, and the pure mineral oil ink has the greatest reduction, i.e. the greatest ink setting. They seem also to have some whole-ink penetration because of the highest strike through among the mineral oil inks (Figure 69) but they also have rapid and great solvent separation which decreases set-off.

Conclusions:
So, explanation for the exceptional performance of the inks in the case of set-off can be found more likely from the formulae of the inks i.e. the share of low viscosity oil than from the viscosity measured. Set-off has not been predicted successfully by the measured viscosity of the inks. In addition, viscosity of inks and strike through can not explain the difference between the vegetable oil inks and the mineral oil inks regarding set-off (Figures 72 and 73) either. Strike through is only slightly higher with the vegetable oil inks than that of the mineral oil inks at the same viscosity and ink requirement (Figures 69 and 70) and set-off of the vegetable oil inks is notably lower than that of the mineral oil inks at the same strike through (Figure 72).

The lowest viscosity vegetable inks containing no high viscosity oil seem to penetrate into the interior of paper during (whole-ink penetration) the nip dwell time. The mineral oil inks stay on the surface of paper better. Obviously, the commercial ink stays better on the surface of paper than the laboratory model inks having the same viscosity measured. It has a lower ink requirement and less strike through than the others do, and it has a relatively high set-off.

The results of Test series 4 has shown that there are unknown factors in these model ink groups affecting the ink setting measured by the set-off change in the given time period, e.g.:

- Vegetable oil in printing ink increases the polarity of the ink and mineral oil increases the dispersion component of the surface energy of the ink /112/. Fibre surfaces have a polar nature because of the hydroxyl groups and other functional groups. This could explain the better setting properties of the vegetable oil inks and also their slightly higher strike through at the same viscosity compared to mineral oil inks. The polarity of a liquid improves its spreading to a polar surface.
- Another reason could be the differences in the internal cohesion forces of the inks. E.g. the surface of carbon black pigment has a non-polar nature. Thus, it could be supposed that polar vegetable oil could separate easier from that kind of mixture than non-polar mineral oil. However, there are dispersing agents used to give a good dispersion for the carbon pigment. These can change the surface chemical nature of the dispersion. The components of ink interact with each other and it makes this kind of the multi-component system complex.

The viscosity of the model inks are connected inter alia the relation of high and low viscosity oils. These oil components also dominate ink flow in the printing nip and the solvent release i.e. ink setting after the nip. Viscosity has a connection with ink setting via the type of solvents. The viscosity of the ink layer may also affect solvent diffusion through the ink layer thus speeding up or slowing down the ink setting. In addition, the additives used in production inks change the rheology of the ink and the interaction of the ink components.

6.4.6 Ink setting theory

Ink setting in CSWO printing means that the mobile phase (solvents) releases from ink pigment and resin. Resin becomes harder and binds pigment with paper surface. The ink layer becomes thinner and also less smearing. (Depending on the type of the resin, it is also possible that the ink layer during a certain stage of setting becomes more adhesive.) However, some solvent, especially high molecular weight stays with the pigment and the resin and the ink does not dry completely.

Ink setting can be seen by following the reduction of set-off during the time period after printing. Thus, ink setting (*IS*) as the change of set-off (*SO*) in time (*t*) can be described by an equation (24):

(24) $IS(t) = d(SO)/dt$

The regression analysis, *SO* as the function of the square root of time (*t*) from the results in Figure 29 gives the experimental equation (25):

(25) $SO = a * e^{-b\sqrt{t}}$

where *a* is $SO_{t=0}$, and *b* is the solvent release factor for a paper and ink combination.

In Table 19, the parameters of the equation (25) are calculated from the results in Figures 29 and 64. The statistical significances R^2 are high. The parameters *a* and *b* do not cross-correlate statistically significantly. The solvent release factor *b* varies in the range 0.101-0.139 with the papers and the ink used (Figure 29), and in the range 0.062-0179 from Figure 64 for inks and the paper used. The over 75 % DIP containing papers DIP A and DIP B had the highest value of *b* among the paper samples indicating the fastest ink setting. The INK 2 had highest viscosity but one of the fastest ink setting. This means that viscosity does not dominate setting of these inks, and this also points out that the interaction of ink components and the spreading ability of the ink solvents are in these cases more important than viscosity. But, it does not mean that viscosity is not important in ink setting at all.

Table 19. The factors a and b and R-square according to equation (25) from the results of Figures 29 (papers) and 64 (inks). INK 1 and INK 2 are commercial samples. Ink setting values IS(t) are calculated at the delay time 1 s.

Ink sample	***a*** D	***b*** $1/\sqrt{s}$	**R-square**	**IS(t)** D/s	**Paper sample**	***a*** D	***b*** $1/\sqrt{s}$	**R-square**	**IS(t)** D/s
363/1	0,62	0,18	0,986	-0,092	Virgin A	0,63	0,11	0,997	-0,064
363/2	0,70	0,09	0,986	-0,059	DIP A	0,41	0,13	0,975	-0,046
363/3	0,45	0,14	0,926	-0,055	DIP B	0,40	0,14	0,991	-0,049
363/5	0,68	0,09	0,978	-0,055	TMP+DIP	0,64	0,11	0,981	-0,065
363/6	0,57	0,16	0,993	-0,076	Virgin B	0,56	0,10	0,974	-0,051
363/7	0,69	0,09	0,966	-0,056					
INK 1	0,62	0,06	0,879	-0,036					
INK 2	0,75	0,15	0,993	-0,094					

Set-off is a function of the square root of time. This comes from the wetting of the ink solvents with the paper surface and it is parallel to the flow speed controlled by surface forces like the capillary forces. Also equation (13) (Chapter 4.5.1), the ink solvent flow through the filter cake forming during ink setting has given this relation for time; in addition, the flow is dependent on the inverse of the square root of ink viscosity in this equation.

But, we have different viscosities: 1) initial ink viscosity, 2) changing ink viscosity due to solvent release and 3) the viscosities of the ink solvent components. Commonly, the equations describing ink flow and ink setting have only one factor for viscosity and it is understood as the initial ink viscosity. However, according to the theories of flow, viscosity is the viscosity of the flowing liquid. Thus, thinking the ink setting as the solvent release and the flow of solvents into the interior of paper, the most important viscosities are the viscosities of solvents. The initial and the changing ink viscosity are important for the whole-ink flow and also, for the solvent flow inside the ink layer, in the complex situation in which also the filter cake forming takes place.

As the derivative of Equation (25) can be developed for the ink setting *IS(t)*:

$$(26) \qquad IS(t) = -\frac{ab}{2\sqrt{t}} * e^{-b\sqrt{t}}$$

where *a* is the set-off at zero delay time, *b* is the solvent release parameter and *t* is the time.

When *t* approaches zero or infinity, *IS(t)* approaches infinity and zero respectively. Immediately after the printing nip, this indicates a very high ink setting activity, which slows down in time. In Table 19, the ink setting values *IS(t)* are presented at the delay time 1 s.

From the ink point of view, ink setting is dependent on the dispersion stability of ink e.g. viscosity, temperature and interaction of the ink components: pigments, solvents, resins and additives. Ink setting is also dependent on paper properties especially on the specific surface area of paper. In addition, the spreading ability of the ink solvents onto the paper surface forms the initial force for the spreading. Thus, the factor *b* in the equations above should be a complex function.

6.4.7 Summary of the ink studies

The measured viscosity alone could not explain the deviation in the values of ink requirement and strike through, especially in the comparison of the model mineral oil inks and the commercial ink. The model inks rich in low viscosity oil have especially high ink requirement and strike through. There are two components causing strike through: 1) ink solvents (oil) absorbed into the interior of paper filling in the fine capillaries thus decreasing the opacity of paper, and 2) ink pigments penetrated deeper into the roughness profile of paper and in suitable cases into the interior of paper. Low viscosity ink (and especially if only low viscosity oil is used) increases this latter probability.

In the whole-ink absorption, the viscosity dominates, especially if there are no big differences in the contact angle between ink and paper. But, if the solvent (oil component) separation explains the results, as it seems to in the most cases, then the viscosity of the ink is not the main factor in ink setting.

An exponential equation for set-off as a function of time is created including a factor for the solvent release. Ink setting is defined as the change of set-off during the delay time after printing. It is the derivative of the set-off function of time. The units for the ink setting and for the solvent release factor are [D/s] and $[1/\sqrt{s}]$ respectively.

The solvent separation can be explained by the surface spreading by the secondary flow along the micro surfaces and the open sided capillaries on fibres, and also with the solvent flow via the finest surface capillaries <0.5 µm into the interior of paper. This size of capillaries or other kinds of spaces inside paper are also active by causing light scattering and increasing opacity, thus preventing print through. However, becoming filled by ink oil they lose that ability and print through increases by strike through, as has also been presented in the literature studied.

The results show clearly the absorption of ink or ink oils, but the mineral oil inks and the vegetable oil inks are different. The production ink performed differently to both of them. Penetration of the vegetable oil inks in the printing nip is more dependent on viscosity than that of the mineral oil inks. Penetration of whole-ink to surface voids of paper is obvious, but there might also be some capillary penetration especially in the case of the lowest viscosity vegetable inks containing no high viscosity oil.

Polarity of vegetable oils may improve the solvent (oil) separation from non-polar pigments (carbon black) and speed up the spreading of the oil into the surface pore structure of paper thus giving a better ink setting for the vegetable oil inks.

It is presented that ink can perform with a different or even significantly higher than the measured viscosity during the printing nip dwell time. This apparent viscosity might be an important controller for ink requirement and strike through caused by whole-ink penetration. In the printing nip, there seem to be different shear rates for ink while ink transfer takes place to rough uncoated newsprint, at quite high but also low shear rates. In production printing, the time from the inking train to a plate-to-blanket nip and the time to a printing nip is short (about 0.1 + 0.1 s) but in laboratory printing this is longer (about 5 s) because of the separate inking of the printing disk. This can cause differences with thixotropic inks between laboratory and production printing. In addition, in laboratory conditions, the ink temperature is lower in comparison with viscosity measuring in this test series 23 °C vs. 30 °C. The higher temperature is close to conditions of production printing.

With the experience of these laboratory inks, however, one ought not to make direct conclusions regarding commercial inks. Especially the production ink, being a reference, performed differently in the tests. Maybe, e.g. the additives and binders, being added into the commercial ink for adjusting the ink rheology, have given these special properties to the ink.

6.5 Microscope study

6.5.1 Unprinted paper surface

A surface picture of one virgin TMP paper (Figure 74) and one DIP paper (Figure 75) are made with a scanning electron microscope /2/. The differences in the structures are visible. The strong TMP fibres dominate the surface of the virgin paper. In addition, the whole structure looks coarse and the fines areas between the fibres seem to be more closed than the surface of DIP paper. In this comparison, DIP paper had:

- slightly less ink requirement and slightly higher brightness (opposite to other cases)
- slightly higher PPS roughness (Bendtsen roughness about same)
- Bendtsen air permeability approximately the same
- 20% lower PPS compressibility
- 38% lower Pira PPST compressibility (change in contact area)
- 40% lower contact area (Pira PPST)
- 30% less short delay (2.5 s) set-off and 50% less long delay (60 s) set-off.

6.5.2 Printed paper surface

With the microscopic illustration below, the CSWO printing on the surface of uncoated newsprint and the set-off type of smearing caused by ink transferred from the printed area to the counter paper are discussed.

Incomplete ink coverage can be seen on the pictures in Figure 76. The uncovered areas are the topmost fibres (red arrow on upper picture on the right) which are cleaned of ink by nip pressure, or deep and steep holes, which have had no contact with the ink layer on the offset blanket. In this kind of surface details, the ink coverage is not improved by increasing ink volume on the blanket. Instead, the kind of areas as seen on the bottom picture on the left (yellow arrow) may have better coverage with a greater amount of ink. In addition, it can be helped by higher printing nip pressure, good conformability of the offset blanket, and by lower viscosity of ink. The holes of the same picture on the upper left corner (white arrow) are covered by ink. These places may have been helped by compression of the adjacent surfaces in the printing nip. The large hole in the centre of the upper picture on the left is about 10 µm deep according to SEM stereo picture analysis.

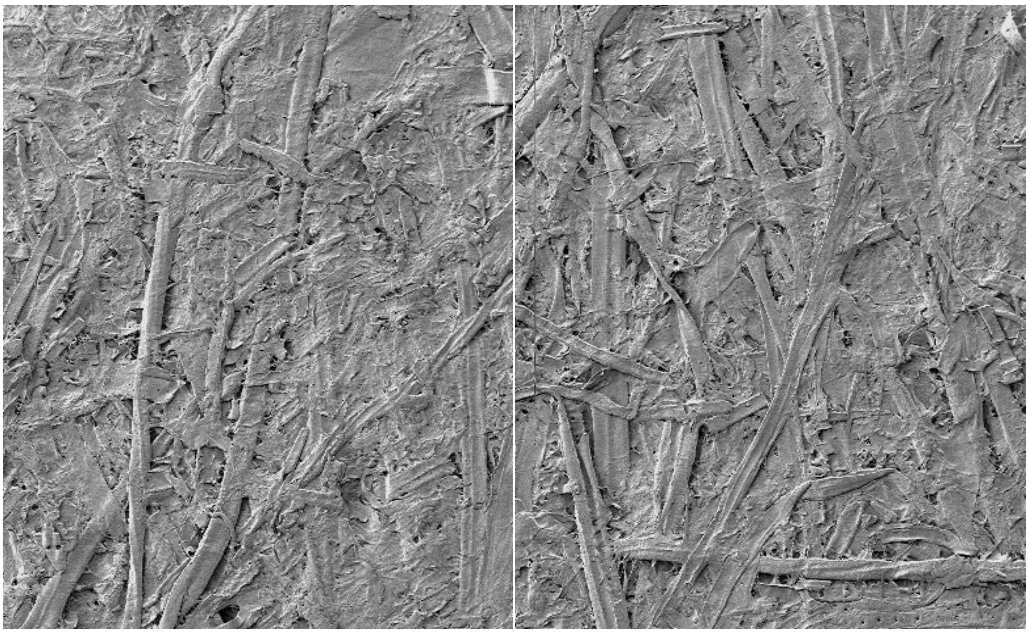


Figure 74. Virgin paper surface, about 100x /2/.

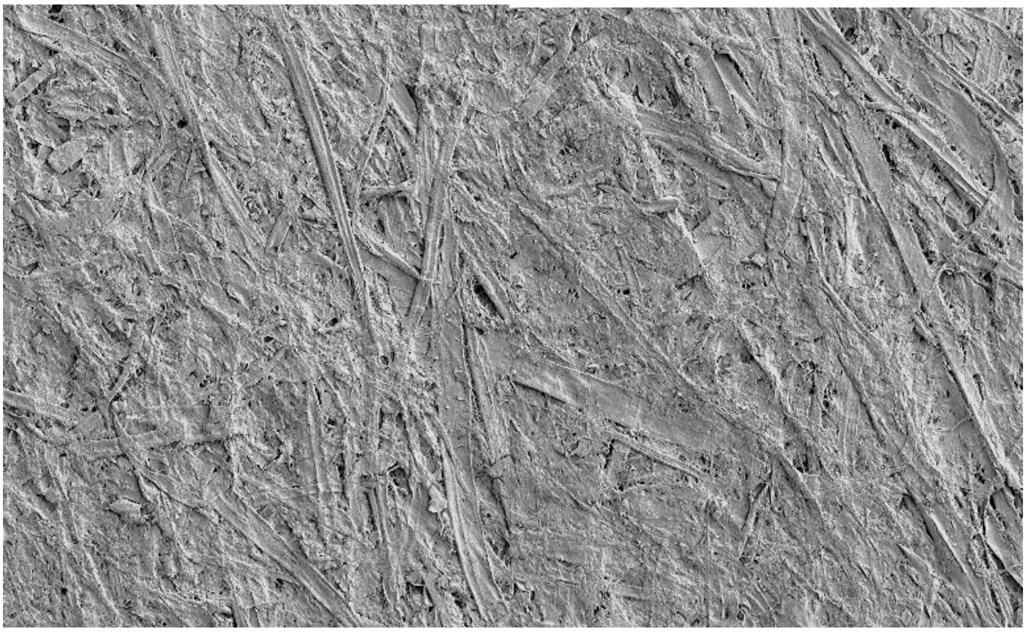


Figure 75. DIP paper surface, about 100x /2/.

If viscosity of ink is very low, then ink can flow into the steep holes, where its ability to absorb light is weaker. Also, the thick ink layer as in the adjacent area of the fibre cleaned of ink (red arrow) is not as effective for absorbing light as a thinner ink layer per mass unit. The thick ink layer has also cracked.

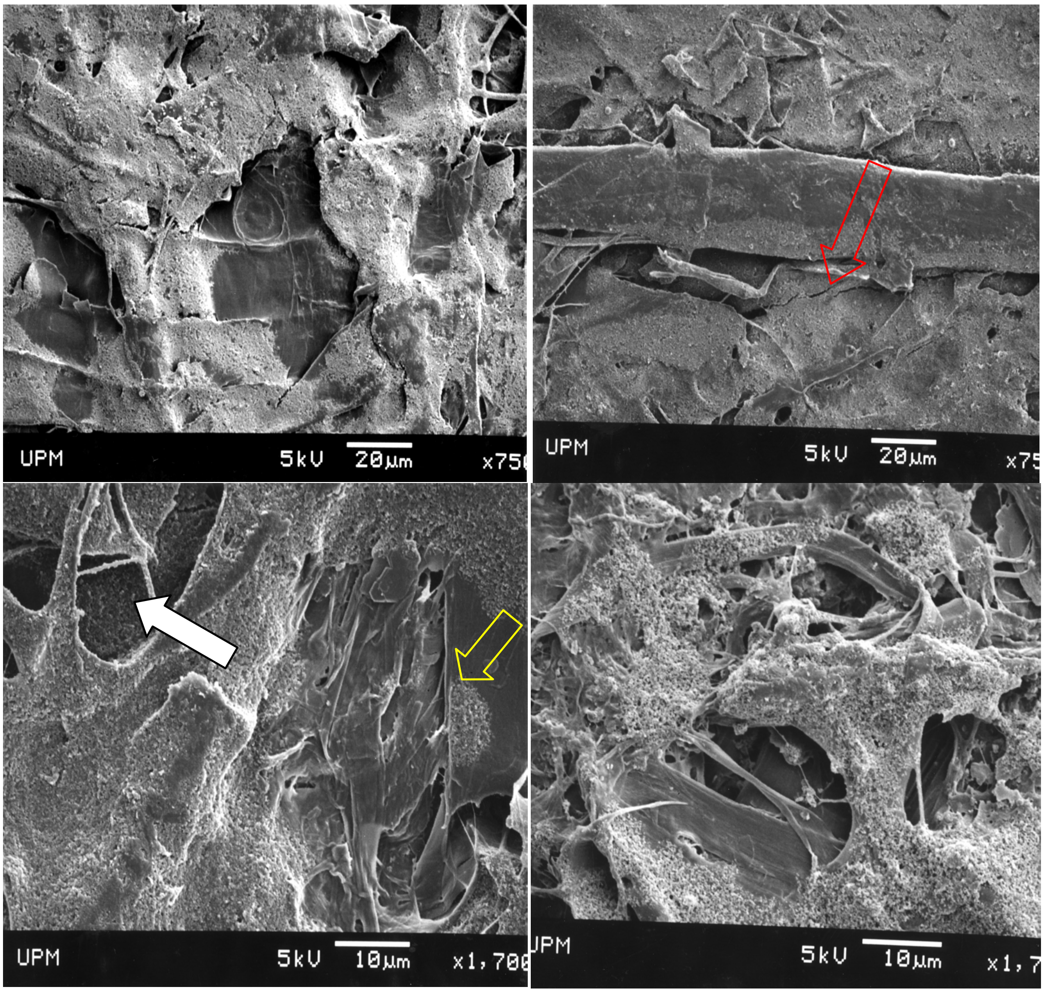


Figure 76. Pictures of the printed surfaces of newsprint, kV is the acceleration voltage /46/. Ink can be seen as a brighter substance on the fibrous material. Note the scale marked on the bar below the pictures.

The surface of newsprint in these pictures is very rough and there are lots of micro surfaces (micro mirrors) which scatter the light directed towards the paper surface. This decreases print density and increases ink requirement. The size of the pores actively influencing solvent separation are about 0.1-0.5 µm in diameter. These capillaries are invisible on the scale of the pictures and are covered by the ink pigment substance.

<u>A set of cross sections</u> of printed newsprint taken with a Reichert 2050 Supercut Microtome and a light microscope is shown in Figure 77. Black ink film forms the thin line on top of the cross sections following the roughness profile. Only minimal ink pigment penetration into the paper can be seen (cross section 3). We should not draw any exact conclusion about the roughness differences of different paper samples. Samples are small and the local roughness variation is large.

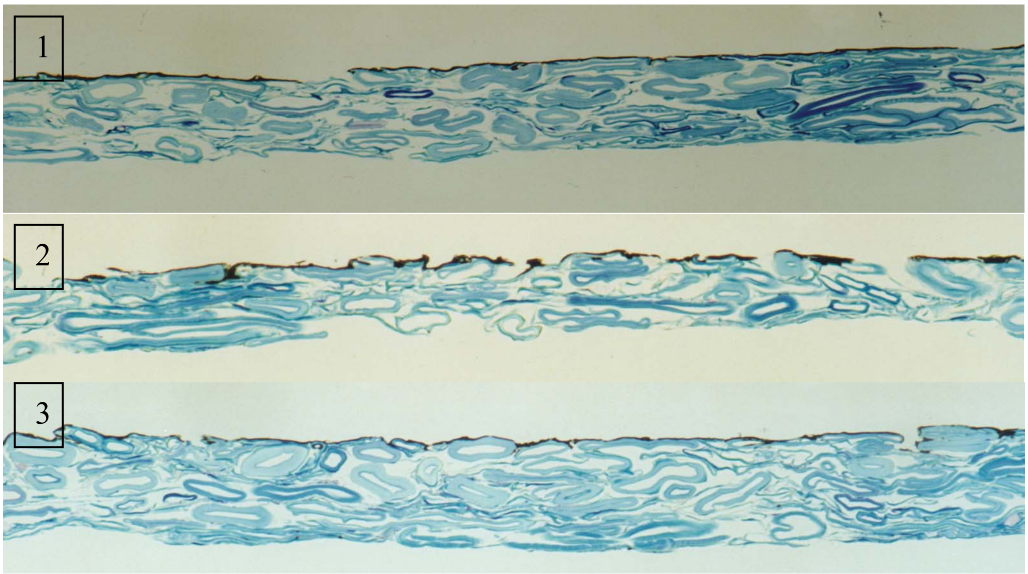


Figure 77. Cross sections of printed newsprint. The black line on the top of the sections is the one colour black printing ink film. Magnification approximately 350x /46/.

6.5.3 Optical microscope pictures of set-off prints

In practice, the same paper as printed is also the facing sheet in set-off situations. Set-off takes place at the places where there is contact between the surfaces. The contact points in a set-off print seem to be distributed quite randomly over the surface. At a reasonable print density level, the scale of ‘wavelength’ is a few hundred micrometers.

<u>Analysing the set-off print</u>
Figure 78 illustrates a set-off print on a coated counter paper in a Prüfbau test. The picture of the set-off caused by the fibre matrix contains double lines (block arrow). These are created by the ink being pushed away from the fibre surface towards the edges of the fibres as presented in chapter 4.2.5. In addition, quite strong single lines forming a special type of set-off can be seen. These are caused by the collapsed fibres, which have a groove in the middle, also called ‘dented fibres' /46/. In this case, the ink transferred onto the fibres is not moved to the edges of the fibres by nip pressure. The depth of the groove can be 3 µm (measured on an SEM stereo picture /46/), which is about the same as the thickness of the ink layer on an offset blanket. Because a fibre cannot absorb the ink vehicle, the ink could lay on the fibre surface for a long time potentially causing set-off. However, this ink may set in time by utilising the open sided capillaries on the fibre surface and the 'secondary flow' explained in chapter 5.4.

The contact between the printed surface and a coated counter paper gives a clear picture. When set-off takes place onto the same paper as printed, the spatial roughness profile is ‘doubly important‘. Set-off print on the ‘own paper’ with high roughness does not contain either clear single or double lines. This is because the two rough surfaces are pressed against each other. Two facing fibre matrixes form a set-off print with broken lines (Figure 79). The contact area is the product of the

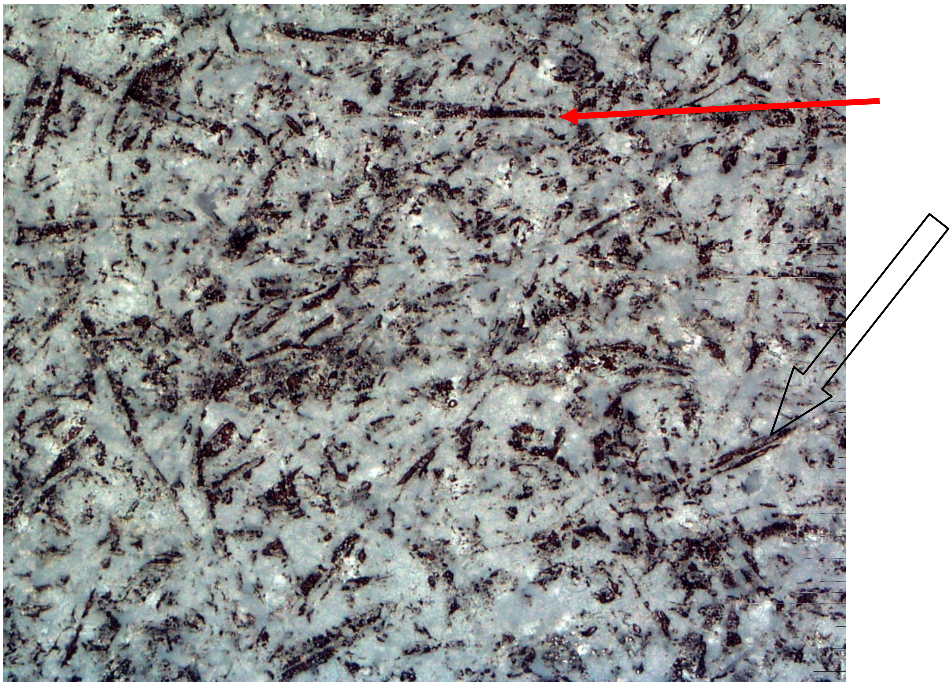


Figure 78. Set-off print on a coated counter paper. Double (block arrow) and single lines (red arrow) can be seen, approximately 60x. (Picture UPM-Kymmene Valkeakoski Research Centre).

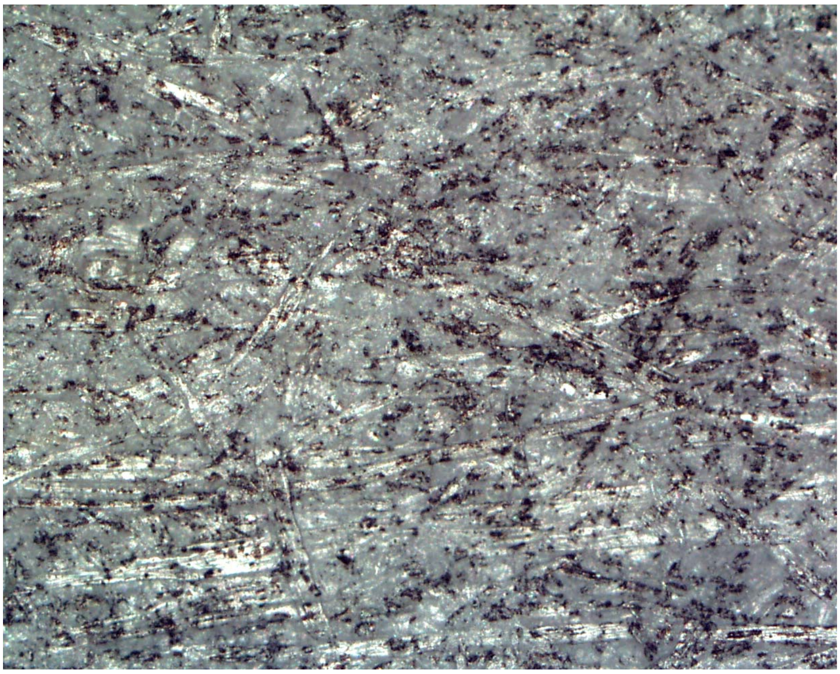
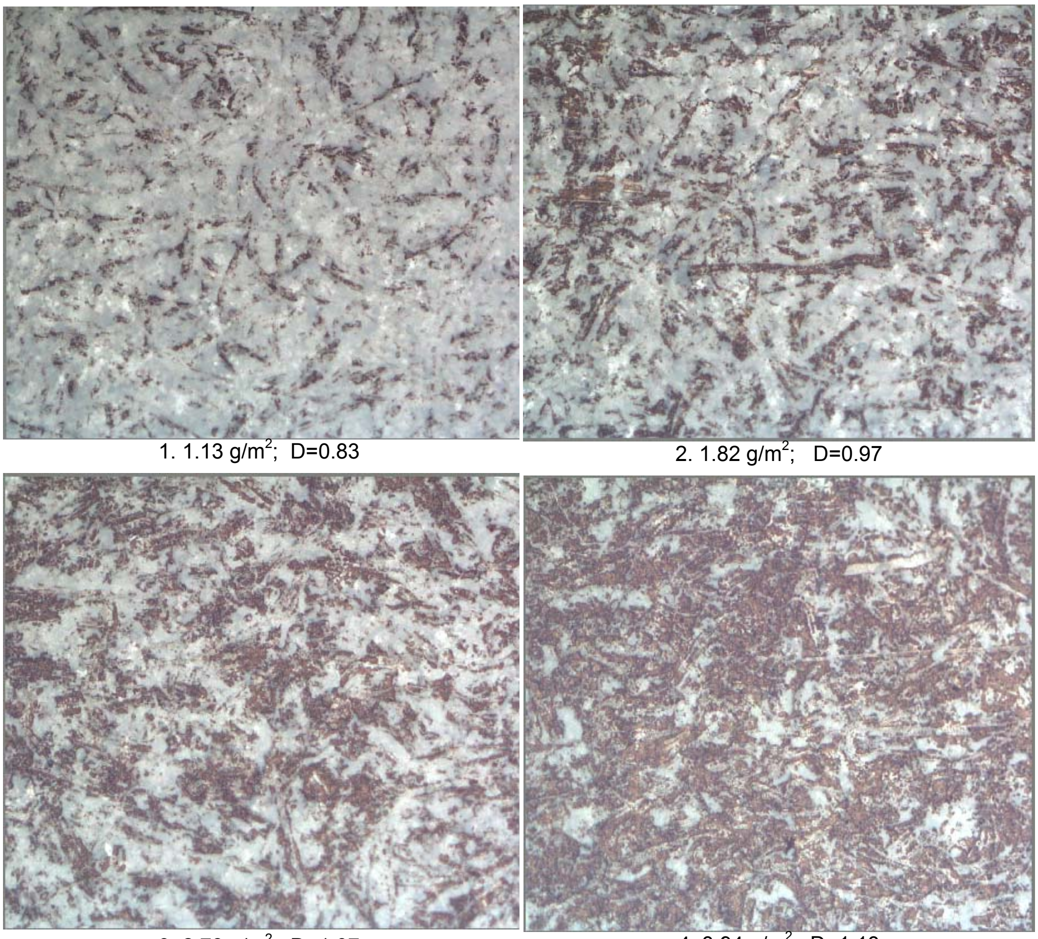


Figure 79. Set-off print on 'own paper' as the counter paper. The surface structure of newsprint can be seen, approximately 60x..(Picture UPM-Kymmene Valkeakoski Research Centre).

two profiles or in this case the profile to the power of 2. In chapter 6.2.9, it was illustrated that the set-off print density was 30% higher on the coated counter paper than on the 'own paper', and the set-off values cross correlate with very high significance (Figure 56).

In Figure 80 on the coated counter paper, the fingerprints of set-off with increasing print density are presented. In the first picture, the set-off print is formed mainly from the fibre matrix of the printed paper. With increasing ink amount the fines areas between fibres also start to give more and more set-off and the amount of that set-off becomes more dominant. The set-off from the fines areas created with higher ink amounts can be explained by too low an absorption capacity of the fines areas. In addition, the thicker ink layer needs more time for setting.

The print density 0.97 D measured with non-polarised densitometer represents a good level for normal newspaper printing. It is obvious that the situation described above is the same for short and long delay set-off, only, after a longer delay, there is less wet ink available for transferring.



1. 1.13 g/m^2; D=0.83

2. 1.82 g/m^2; D=0.97

3. 2.78 g/m^2; D=1.07

4. 3,94 g/m^2; D=1.13

Figure 80. Set-off print of DIP newsprint after 60 s delay time on a coated counter paper at different ink amounts g/m^2 and print densities (D), approximately 35x.(Picture UPM-Kymmene Valkeakoski Research Centre).

6.6 Summary of the experimental work

Testing of printing conditions, pulps, fillers, paper properties, and model inks is reported in the experimental part of this work to get answers to the open questions, which surfaced, from the literature study and from the theoretical comprehension. The set-off phenomenon in CSWO printing is defined as a process. It is dependent on the ink location on and in the roughness profile of newsprint, on the ink setting during the delay time between the printing nip and the set-off situation, and finally on the conditions in a set-off situation, in which a printed sheet is pressed against a facing sheet and the desirable ink transfer takes place. Newsprint and newsink are the main partners in this process.

In the following section, the effects of the most important parameters on set-off are summarized. Some remarks are also made on strike through and print through.

The order of the process parameters

Using Taguchi analysis the order of importance of process parameters for set-off was studied. The parameters were paper (virgin and DIP news), pressure in set-off situation, counter paper, delay time between printing and set-off situation, and ink amount transferred to paper. For the analysis, two levels of the parameters were chosen. Analysis was also prepared at two constant solid print densities.

If the set-off values were interpolated at a constant print density or at a constant ink amount transferred to paper, the order of the printing parameters affecting set-off was not the same. It is because the papers studied had large difference in the ink requirement and the solid print densities and ink amounts chosen for the analysis did not fit exactly with each other. The order of the parameters in Table 20 is an average. Taguchi analysis also pointed out that the variation of importance between the parameters was not large.

Table 20. The order of magnitude of the parameters for set-off from Taguchi analysis; the first is the strongest.

Order	Parameter	Levels	Less set-off
1	level of print density	0.9 D or 1.0 D	0.9 D
2	paper	DIP pulp or virgin pulp	DIP pulp
3	counter paper	'own' paper or a coated one	'own' paper
	time delay	2.5 or 60 s	60 s
5	ink transferred	1.5 or 2.0 g/m^2	1.5 g/m^2
	set-off pressure	10 or 20 kN	10 kN/m

Effect of furnish on set-off

Pulps: The big difference from the set-off point of view was found between DIP pulps and virgin pulps. DIPs were very advantageous for reducing set-off and print-through. The mixture of mechanical and chemical fibres with fillers, and the relatively short average fibre length made the sheets easy to calender. DIP sheets also had a good ability to set ink.

The virgin pulp, TMP, used in newsprint grades had the opposite properties to DIP. It had a long average fibre length, and the strong TMP fibres were more difficult to calender. Its fines material had a good bonding ability forming more closed fines areas (good smoothness). TMP created a different kind of surface roughness profile and the compressibility of the sheet surface was greater. The holes close to surface fibres looked deeper.

Fillers used in newsprint and MFS grades improved opacity. They also improved ink setting by decreasing set-off measured after the long delay time. The round shape filler used seemed to be more positive than the platy filler, but the difference was not large. Thus, the use of fillers was positive for decreasing set-off and for reducing print through.

In simulating deinked pulp, reinforced chemical pulp was mixed with TMP resulting in decreasing set-off, both short delay and long delay set-off. Adding fillers to TMP clearly decreased only the long delay set-off (one exceptional point). Also, CTMP had lower set-off than virgin TMP. The CTMP sheet was not so sensitive in calendering as the other pulps having a lesser trend of increasing set-off with growing calendering load.

Effect of paper properties on set-off

The most important properties of paper from the set-off point of view were: roughness, compressibility of the paper surface, surface pore structure or the specific surface area, and brightness.

Roughness of paper is obviously important for decreasing set-off. Stronger calendering decreased roughness and increased set-off. The result supports the literature. The nature of roughness is also important. The depth of the surface voids extends to 20 µm or more. Deep holes in the surface give high roughness measurements but they do not protect ink against set-off, as ink does not sit in such deep holes.

High roughness is a negative property of paper in a printing nip, causing more uneven ink coverage thus more ink is needed for a target print density. In the tests, the stronger calendering gave better smoothness and lower ink requirement for the sheets. Commonly, less ink also means less set-off. However, the sum effect of higher roughness on set-off was decreasing, although the ink requirement was higher.

Compressibility of paper surface: Compression of the paper surface in the set-off situation increases contacts of ink with the facing sheet, increasing desirable ink transfer. Compressibility is a positive property in the printing nip achieving a more even ink coverage. When less ink is needed for the target print density this means less set-off. However, it was seen in this study that the sum effect of compressibility on set-off was increasing. Among the paper properties measured, compressibility of paper surface gave the best linear correlation coefficients with set-off in most cases (9 from 12) including both relative and absolute compressibility.

Although the absolute compressibility "delta PPS 5-10" decreased the stronger the calendering was, the changes in relative compressibility PPS 5/10 were small. These compressibility changes in calendering gave no clear connection to set-off.

Pore structure of uncoated newsprint can be connected to the absorption properties measured as Cobb-Unger oil absorption. However, Cobb-Unger did not correlate analogically with set-off, and neither does Bendtsen air permeability. Also, the oil porometer measurements did not explain the low set-off values of DIP paper. Instead, the specific surface area (BET) of DIP paper was higher and it had more small capillaries (<1 µm, Hg intrusion) than the samples with high set-off. The long delay set-off of the sheets made of TMP and loaded with fillers decreased the higher the loading was.

Brightness: The brightest MFS grade had 12% higher brightness than DIP newsprint. Besides the higher roughness of DIP paper, the brightness difference caused a 40% higher ink requirement for DIP news and about the same set-off level for MFS grade and DIP news.

Ink requirement

Ink requirement is calculated at a given print density. In this study, 0.9 and 1.0 D values were used and measured with a non-polarized densitometer. The value 0.9 is close to the level of practical printing.

According to a stepwise regression analysis, about 90% of the variation in the ink requirement of the 18 mould sheet samples at 1.0 D was explained with three paper properties: relative surface compressibility 75.9%, roughness 7.4% and Y-value 6.2%. The ink was a commercial newsink.

In 20 model inks and 1 production ink, the ink requirement correlated significantly (R^2=0.83) with the inverse square root of the low shear rate viscosity (Kozeny's equation (10)). However, without the conversion, almost same significance of linear correlation was found between ink requirement and low shear rate viscosity. The production ink was the furthest from the trend line. Transforming the viscosity of the production ink to the trend line doubled its viscosity value and this was called the 'apparent viscosity' in the printing nip. With high shear rate viscosity, the mineral oil inks and the vegetable oil inks performed differently. The former had a higher ink requirement at the same ink viscosity. In addition, with the vegetable oil inks, the low viscosity oil fraction correlated linearly with the ink requirement and with a high significance (R^2=0.99; n=9). Mineral oil inks performed similarly but with higher deviation.

Ink setting during delay time

In the first 10-15 s after the printing nip, set-off reduced noticeably and continued to decrease more slowly thereafter. The rate of reduction depended on the paper structure and ink properties.

Ink setting is defined as the change of set-off during the delay time. For set-off, an exponential equation is created, in which set-off is the function of the set-off at zero delay time and the square root of time including the solvent release factor. Ink setting is then the derivative of the function. It approaches the definite value when time approaches zero indicating the high setting activity immediately after the printing nip. The solvent release factor is a constant for one ink and paper combination and combines all the properties of ink and paper affecting solvent release from the ink layer into paper structure such as interaction of ink components, viscosity and surface tension of ink solvents, contact angle of the solvents with paper and the specific surface of paper.

Set-off situation

Raising the set-off pressure from 10 to 20 kN increased set-off 20-30% or about the same as if the ink amount transferred had been changed from 1.5 to 2.0 g/m^2. The result stresses the importance of the low surface compressibility of a sheet for low set-off.

The facing paper in newspaper production is the same paper as printed ("own paper"), but it can also be a smoother paper grade e.g. if a hybrid printing machine (CSWO+HSWO) is used, or inserting separately printed advertisements. The smooth coated counter paper in the Prüfbau tests gave an approximately 30% higher set-off levels than the "own paper".

Recommendations for further investigations

- To verify in practice the flow of oil in the open-sided micro capillaries on the surface of uncoated newsprint.
- To measure the pore structure of the fines area from the ink setting and set-off point of view.
- To create a dynamic method to measure the surface structure of rough uncoated paper from the CSWO printing point of view. Further, to evaluate, what is the importance of the average distance from one strong set-off point to the other, approximately several hundred micrometers, and its relation to the surface compressibility.
- To investigate the role of the interaction of the ink components in ink setting.

7 CONCLUDING REMARKS

The main findings of this study are:

MOST IMPORTANT PARAMETERS FOR INK TRANSFER
The most important parameters for ink transfer in coldset web offset (CSWO) printing are, besides the rheological properties of the ink, the offset rubber blanket and the roughness profile of newsprint, and their performance under pressure in the printing nip.

The printing blanket has two functions in ink transfer: 1) because of its soft rubber surface and the pressure in the printing nip the blanket conforms partly with the roughness profile of the paper; 2) because of its compressibility the blanket follows the thickness variations of the paper on the formation scale. This type of printing blanket increases the effective surface area of uncoated newsprint on which the ink is distributed, i.e. the ink coverage. The actual surface is larger than the nominal surface (measured by a ruler) because the offset blanket conforms with the roughness profile, transferring ink deeper into the profile. In addition, the actual surface is increased due to the micro-roughness of paper, at an approximate scale of below 1 micrometer. The surface voids of the micro-roughness can be filled by ink, and this ink cannot contribute to the splitting of the ink film when the paper leaves the nip. These two points may explain most of the asymmetry in the splitting of the ink film, since a major part of the ink is transferred to the paper and a minor part stays on the blanket, even though the rough surface of the paper is not completely covered by ink. The immobilised ink is defined as the ink, which does not contribute to the splitting of the ink film. Then, in CSWO printing, in which a small amount of ink is used in practice, the penetration of ink into the interior of the paper plays a minor role in the immobilisation.

Roughness and surface compressibility are contradictory properties of newsprint in relation to ink transfer. A rough paper allows less contact with the thin ink film in the printing nip, which means less effective ink transfer and a need for more ink in order to reach the desired level of print density. In contrast, a paper with good surface compressibility results in reduced roughness under pressure in the printing nip, which means improved ink transfer.

The viscosity of CSWO laboratory model inks used in the present study were found to affect the ink requirement and print-through (strike-through). However, in terms of viscosity, production inks performed differently from laboratory model inks, because the model inks did not contain all the substances that are used to control the rheology of production inks. Thus, the performance of model inks cannot be used as a basis for direct conclusions on how production inks perform in CSWO printing. The apparent viscosity of non-Newtonian inks in a printing nip may vary because of variations in shear stress. CSWO inks are shear-thinning, viscoelastic, and also thixotropic. For this reason, the viscosity of the ink does not decrease as quickly as the shear stress increases during the short time that the ink is exposed to the nip pressure.

The amount of CSWO ink in the printing nip (on the blanket), roughly 3 g/m2, does not penetrate to any noticeable extent into the interior of the paper. The ink pigment stays on the roughness profile on which the ink is distributed by the conformable printing blanket. The penetration of ink in single-colour printing is mostly prevented by:

- lack of ink for filling larger surface voids
- too high ink viscosity to allow it to penetrate into fine capillaries
- lateral flow of ink caused by the hydraulic pressure in the ink layer. The hydraulic pressure is not constant over the printing nip because of incomplete contact between the ink film and the paper surface
- thixotropy of ink
- too large ink pigment particles, preventing them from penetrating into fine capillaries.

Because of coverage and penetration, the image of cross sections of multi-colour pictures is different from that of single-colour pictures. In normal newspaper printing, the tonal coverage in a solid 4-colour black area is approximately 240-280%. If more ink is transferred to the paper, the probability of better ink coverage and greater ink penetration increases. The ink layer printed first on the paper is pushed deeper into the surface voids by the following ink layer. This increases the ink coverage area. In addition, the ink which is squeezed away from the topmost fibre surface towards the edges can be pushed deeper into the gap around the fibre, resulting in increased ink penetration.

MOST IMPORTANT PARAMETERS FOR SET-OFF

The most important parameters for set-off in CSWO printing are:

- the amount of ink transferred to the given paper
- the type of paper: newsprint made of deinked pulp (DIP) or virgin mechanical pulp (at the same roughness)
- delay time after printing and before the set-off situation
- pressure in set-off situation, e.g. in a folder
- the properties of newsprint

Less set-off can be achieved by using less ink, a longer delay time, lower pressure e.g. in the folder, and a newsprint made of DIP and calendered to relatively high roughness. Higher pressure in the printing nip transfers the ink deeper into the roughness profile of the paper, and a greater volume of low-viscosity oil added to the ink improves ink setting. These two parameters have a minor effect on set-off.

The roughness profile of uncoated newsprint can be divided into four areas of ink transfer and set-off. The dividing profile height between these areas depends on the width and steepness of the voids.

1. The contact surface area (mainly the topmost fibres) absorbs most of the nip pressure. According to calculations made in this study, the pressure against the topmost fibres can be of the magnitude of 50 MPa. On the contact surface, the ink flows laterally towards lower-pressure areas.
2. The upper void area where ink is transferred and the ink may cause set-off.
3. The lower void area where ink can be transferred because of the conformable blanket and compression of the paper surface, but where there is no contact between the ink and the facing sheet in the set-off situation, and accordingly, no set-off.
4. The deepest void area where no ink is transferred. Consequently, this part of the roughness profile leads to increased set-off because of the increased need for ink, so these voids should be avoided.

These four areas (surface voids) can be defined using image analysis and topographical maps, and separating the areas, which cause set-off from the areas, which cause no set-off by aid of the image of the set-off print.

The surface structure of uncoated newsprint is complicated from the point of view of ink setting. In this study, the surface was divided into

1. the fibre area and
2. the fines area between the surface fibres.

Excluding fibre pits and possible fractures, the fibre area is virtually closed to absorption of newsprint ink and its solvents. Water applied with the fountain solution on paper can open the wall pores of the surface fibres. However, because of the relations between surface energies, the oils contained in printing ink cannot compensate for the water in the wall pores. The fines area is porous and can absorb the vehicle, i.e. setting ink. On a fibre, newsink can set slowly through surface wicking, through open-sided capillaries (grooves on fibre surfaces) and so-called secondary spreading, in which the thinnest part of the vehicle first wets the surface, with the more viscous oil components then following them (probably by diffusion) into the interior of the paper.

Set-off increases as a function of the amount of ink transferred to the paper. With a smaller amount of ink transferred, set-off is dominated by the topmost fibres on the newsprint's surface. With a greater amount of ink, the fines area between the fibres also affects set-off; the more ink applied on the paper, the greater the effect on set-off.

Newsink is more likely to set on uncoated newsprint if the solvent is separated from the ink than if it is not. The total-ink flow promoted by capillary forces is prevented by

- the ink pigment (and filler) particles, too large to flow with the ink vehicle into the open-sided capillaries and through fine capillaries into the interior of the paper
- a "filter cake" forming above the opening of a capillary as a result of solvent separation
- a lack of ink, preventing the necessary continuous capillary flow
- thixotropy of ink.

The ink layer becomes less smearing and thinner if the solvent is separated from the ink. A thinner ink layer can be more effectively deposited on the roughness profile without contact with the facing paper. In this way, the probability of set-off decreases.

The exponential equation for set-off as a function of the delay time after printing has been developed. It fits with the high statistical significance to the results printed with Prüfbau laboratory printing press. The ink setting is the derivative of the set-off equation. These equations include also a factor for the solvent release, which is a constant for one ink and paper combination but is dependent on all the ink and paper properties affecting the solvent release.

OPTIMISING THE SURFACE OF UNCOATED NEWSPRINT

The most important properties of uncoated newsprint for set-off in CSWO printing are: optimised roughness, low surface compressibility, high specific surface, good absorption ability of the fines area (high proportion of fine pores <1 μm) and uniform formation (no high-density calendering spots).

Newsprint made of deinked pulp (DIP) has resulted in less set-off both after short and long delay times in comparison with newsprint made of virgin mechanical pulp. The reasons for this are the following:

1. Because of its relatively high chemical pulp content DIP-based newsprint has a lower surface compressibility, which results in less contact with the facing sheet, and thus, less undesirable ink transfer to the facing sheet.
2. Fine fillers, especially those originating from recycled coated magazine paper grades, create fine pores in the interior of newsprint, resulting in improved ink setting through solvent separation. This has been reflected in a greater relative decrease in set-off during longer delay times.

In addition, roughness is more evenly distributed on the surface of DIP-based newsprint (on average shorter and more flexible fibres in comparison with virgin paper), which makes it possible to optimise calendering for CSWO printing.

Roughness, surface compressibility and bulk influence set-off, ink requirement and print quality. In this connection, DIP-based newsprint has certain advantages over virgin mechanical pulp-based newsprint. In addition, the ink requirement correlates with set-off and print quality.

Bulk has no direct effect on set-off, ink requirement or print quality, but, being a measure of calendering, it does influence these properties indirectly via the paper's roughness and surface compressibility. DIP-based newsprint can be more easily calendered to lower bulk than virgin mechanical pulp-based newsprint. If bulk (and grammage) is assumed to be the same, the roughness of DIP-based newsprint is higher and its compressibility lower than those of virgin mechanical pulp-based newsprint.

Roughness and surface compressibility have opposite effects on set-off, ink requirement and print quality (+ increases, - decreases):

	Increasing roughness	**Increasing surface compressibility**
set-off	-	+
ink requirement for the target print density	+	-
print quality (contrast in dark tones and evenness of the solid print area)	-	+

A higher ink requirement means that more ink has to be applied on the paper to reach a given print density, and more ink leads to increased set-off. However, in many cases, the ink requirement and set-off have shown a negative correlation. This can be explained by the higher roughness and/or lower compressibility of the paper samples, which have required more ink. Higher roughness and lower compressibility result in decreased set-off despite the greater amount of ink on paper.

The effect of roughness and surface compressibility on the ink requirement impairs their favourable effect on set-off. However, as a sum effect, higher roughness and lower compressibility reduce set-off.

Though the compressible and conformable offset blanket compensates for the roughness of paper quite well, too high roughness reduces print quality, while decreasing the contrast in dark tones and increasing the unevenness of the solid print area. This means that roughness should be optimised to reach good print quality but to avoid disturbing set-off.

A common tendency in newspaper printing is to use higher inking levels to achieve better print quality. This causes a trend towards rougher newsprint as a means to control set-off.

The good absorbency of the fines area of newsprint and its greater specific surface allow the ink vehicle to flow into the interior of the paper, thereby improving ink setting and decreasing set-off after a long delay time. Filler loading can be used to improve the absorbency of newsprint. The total loading is more important than the type of filler, i.e. whether its particles are platy or spherical. The filler loading improves ink setting. For this reason, the effect of the filler loading on set-off can only be seen after a long delay time.

Higher brightness of the facing sheet makes set-off more visible because of the higher contrast between paper and set-off print. On the other hand, the higher brightness of the printed sheet gives an opportunity to use less ink, which reduces set-off. If a smooth coated paper is used as a counter-paper in the set-off test, the difference in brightness between the papers (other properties being constant) causes a greater difference in set-off compared to a situation where the counter-paper is of the same quality as the tested paper.

Most of the relationships between set-off and printing parameters are illustrated in Figure 81.

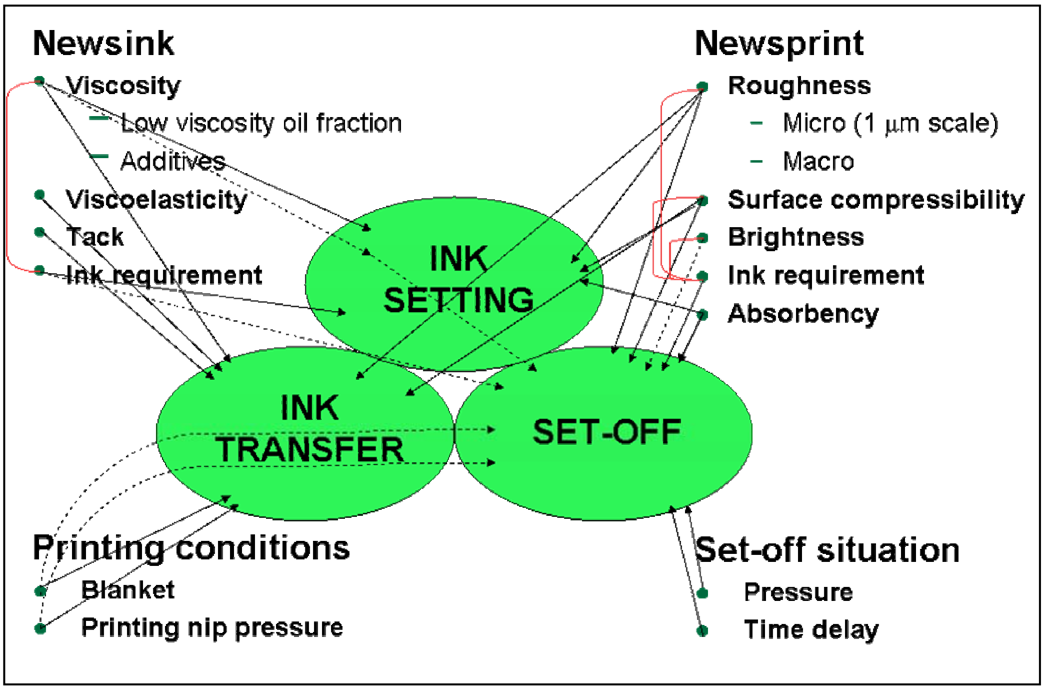


Figure 81. Relationships between set-off and ink transfer, ink setting and other printing parameters. Primary connections are marked with a continuous line, secondary connections with a dashed line.

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STANDARD TESTING METHODS

Hot-disintegration		SCAN-M 10:77
Cold-disintegration		SCAN-C 18:65
Canadian freeness		SCAN-M 4:65
Drainability of pulp (CSF)	ml	SCAN-C 21:65
Chemical pulp contents	%	SCAN-G 4:90
Fibre fractionation (McNett)	%	SCAN-M 6:69 *
Preparation of lab. sheets for testing		SCAN-C 26:76
Testing the lab. sheets		SCAN-C 28:76
Conditioning of samples		SCAN-P 2:75
Grammage	g/m^2	SCAN-P 6:75
Thickness	mm	SCAN-P 7:96
Density	kg/m^3	SCAN-P 7:96
Ash in paper (925)	%	SCAN-P 5:63
PPS roughness	µm	SCAN-P 76:95
Bendtsen roughness	ml/min	SCAN-P 21:67
Air permeance (Bendtsen)	ml/min	SCAN-P 60:87
ISO Brightness	%	SCAN-P 3:93
Opacity	%	SCAN-P 8:93
Light scattering coefficient	m^2/kg	SCAN-P 8:93
Light absorption coefficient	m^2/kg	SCAN-P 8:93
Y-value	%	SCAN-P 8:93
Unger oil absorption	g/m^2	SCAN-P 37-77

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* 16, 28, 48 and 200 mesh

NON STANDARD METHODS

Fibre length and coarseness was measured with Kajaani FS-200 test device. 1.3 g of abs. dry pulp was diluted with 5 litre of water. After separation, 50 ml of this mixture was added to the test vessel and the consistence of the sample was adjusted to correspond to the input number of fibres. The weight of fibres was 15-20 mg at one time, which was controlled with the consistency of the pulp. The number of fibres was about 20000. The sample was stirred all the time. The fibres go through a 0,4 mm capillary tube, and are measured wit an optical module which uses laser beam to determine fibre length. Two parallel tests were done.

Mini-Sommerville shives content was measured as weight % of pulp. Pulp was slushed according to SCAN-M 10:77. Twenty grams of absolute dry pulp was screened using a screen disc with 0.08 mm slots and the percentage of shives was measured.

Ash in paper (550) was determined principally same way as the ash 925 (SCAN-P 5:63), but using the furnace temperature of 550 °C.

Haake viscosity, Haake RT 20 Rotovisco cone and plate viscometer.

Laray viscosity, Laray falling rod viscometer.

SEM images were taken using a JEOL JSM 5800 SEM device, using the SEI detector. The paper surfaces were gold sputtered with an Aga sputter coater device before the imaging using 2.0 kV voltage. The magnification was varied.

EDANA bending length, EDANA 50.2.-80 (The European Disposables and Nonwovens Association).

5.2 Printing parameters and paper properties affecting set-off - Test series 1

Printing conditions 1-4 at Prüfbau, Test series 1.

	1.	**3.**
Ink *)	commercial	commercial
Time delay	2.5s and 60s	0s, 2.5s and 60s
Impression pressure	400 N (10kN/m)	400 N (10kN/m)
Set-off pressure	400 N (20kN/m)	400 N (10kN/m)
Sled coverage	blue rubber #7	blue rubber #7
Printing speed	1 m/s	1 m/s
Printing disc	rubber 40 mm	rubber 40 mm
Set-off disc	metal, 20 mm	metal, 20 mm
Counter paper	own paper	coated
	2.	**4.**
Ink *)	commercial	commercial
Time delay	2.5s and 60s	0s, 2.5s and 60s
Impression pressure	400 N (10kN/m)	400 N (=10 kN/m)
Set-off pressure	200 N (10kN/m)	200 N (=20 kN/m)
Sled coverage	blue rubber #7	blue rubber #7
Printing speed	1 m/s	1 m/s
Printing disc	rubber 40 mm	rubber 40 mm
Set-off disc	metal, 20 mm	metal, 20 mm
Counter paper	own paper	coated

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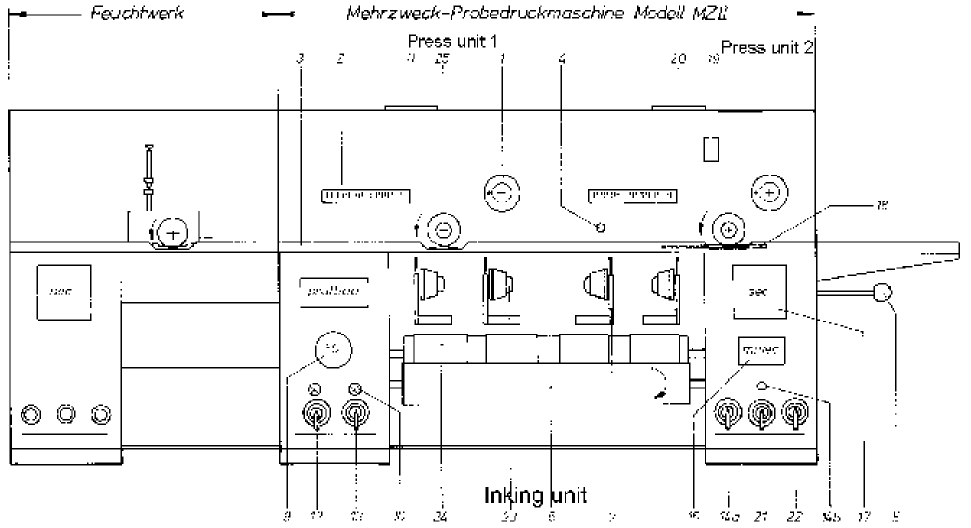
*) Dosering of ink in µl = 100, 70, 90, and 120.

PRÜFBAU TEST PRINTING

The papers were test printed using the Prüfbau printability tester. A total of four test strips with four different ink quantities per sample and per set off interval were printed. The ink quantity was increased stepwise. The quantities were chosen to cover a range of densities from 0.8 to 1.2. The printing was done separately on both sides of the paper.



Prüfbau printability tester. (Feuchtwerk = dampening unit, Mehrzweck-Probedrucmachine = Multi-stage prove printing press)

Ink: Web offset ink (newsink)
Density objectives: 0.8, 0.9, 1.0 and 1.2
Ink distribution time: 30 s
Disc-inking time: 15 s
Disc, material: 4 cm wide rubber in unit 1, and 2 cm wide metal in unit 2
Printing pressure, unit 1: 400 N (10 kN/m)
Counter print pressure, unit 2: 400 N (20 kN/m)
Printing speed: 1 m/s
Time interval between units: 2.5 s and 60 s

The strips were printed in machine direction, and same paper was used as counter paper. The papers were backed by rubber base throughout the printing. The printing disc was weighed before and after the print.

The densities for print and counter-print papers were measured the following day, after one night. The measurements were done by Macbeth RD 918 reflection densitometer. Four different regions were measured. The printed paper, compact print (not exposed to set off nip), back side of the compact ink, and unprinted paper on top of the compact print was measured, as well as the set off print region of the counter, or set off paper. Ten measurements were made from each of the 4 regions. Strike through was not measured, it was determined arithmetically by subtracting show through from print through.

Ink demand, print through, strike and show through, and set off values at given density 1 or given ink quantity 2.0 g/m^2 were interpolated from ink and density information. The standard SCAN-P 36:96 was used when applicable.

5.2 Set-off of different mill papers varying printing conditions - Test series 1

Printing conditions 1

	Point	series	Strip	Delay s	Ink transferred g/m2	Print density D	Set-off D	Show through D	Print through D	Strike through D
1 A	1	1	1	2,5	1,09	0,902	0,266	0,023	0,037	0,014
	2	1	2		1,78	1,066	0,503	0,021	0,050	0,029
	3	1	3		2,51	1,179	0,705	0,024	0,050	0,026
	4	1	4		3,38	1,262	0,857	0,020	0,057	0,037
	5	2	1	60	0,82	0,805	0,117	0,020	0,026	0,006
	6	2	2		1,22	0,918	0,248	0,020	0,037	0,017
	7	2	3		2,14	1,124	0,481	0,022	0,050	0,028
	8	2	4		3,08	1,219	0,721	0,024	0,060	0,036
1 B	9	3	1	2,5	1,20	0,872	0,335	0,021	0,040	0,019
	10	3	2		1,97	1,046	0,511	0,023	0,047	0,024
	11	3	3		2,80	1,148	0,686	0,023	0,056	0,033
	12	3	4		3,89	1,213	0,810	0,023	0,063	0,040
	13	4	1	60	1,14	0,873	0,217	0,022	0,038	0,016
	14	4	2		1,83	1,012	0,372	0,022	0,042	0,020
	15	4	3		2,68	1,121	0,477	0,023	0,050	0,027
	16	4	4		3,79	1,213	0,678	0,021	0,062	0,041
2 A	17	5	1	2,5	1,06	0,815	0,210	0,022	0,040	0,018
	18	5	2		1,88	0,955	0,317	0,019	0,050	0,031
	19	5	3		2,65	1,054	0,451	0,018	0,073	0,055
	20	5	4		3,80	1,126	0,637	0,020	0,098	0,078
	21	6	1	60	1,09	0,818	0,097	0,020	0,039	0,019
	22	6	2		1,83	0,966	0,157	0,022	0,048	0,026
	23	6	3		2,68	1,061	0,304	0,022	0,066	0,044
	24	6	4		3,72	1,122	0,436	0,020	0,101	0,081
2 B	25	7	1	2,5	0,97	0,803	0,153	0,023	0,043	0,020
	26	7	2		1,50	0,949	0,277	0,024	0,050	0,026
	27	7	3		2,27	1,039	0,424	0,023	0,063	0,040
	28	7	4		3,34	1,123	0,593	0,027	0,091	0,064
	29	8	1	60	1,28	0,897	0,090	0,021	0,044	0,023
	30	8	2		1,88	0,995	0,195	0,020	0,050	0,030
	31	8	3		2,61	1,089	0,277	0,022	0,068	0,046
	32	8	4		3,35	1,135	0,393	0,021	0,084	0,063
3 A	33	9	1	2,5	1,04	0,836	0,276	0,030	0,066	0,036
	34	9	2		1,74	1,020	0,426	0,029	0,080	0,051
	35	9	3		2,52	1,143	0,657	0,031	0,095	0,064
	36	9	4		3,35	1,240	0,791	0,028	0,112	0,084
	37	10	1	60	1,14	0,865	0,178	0,031	0,068	0,037
	38	10	2		1,80	1,035	0,353	0,030	0,087	0,057
	39	10	3		2,59	1,149	0,466	0,032	0,095	0,063
	40	10	4		3,38	1,236	0,693	0,033	0,110	0,077
3 B	41	11	1	2,5	1,24	0,886	0,333	0,030	0,067	0,037
	42	11	2		1,89	1,054	0,481	0,030	0,082	0,052
	43	11	3		2,57	1,177	0,671	0,032	0,099	0,067
	44	11	4		3,43	1,259	0,798	0,033	0,113	0,080
	45	12	1	60	1,32	0,899	0,227	0,030	0,070	0,040
	46	12	2		2,02	1,079	0,357	0,029	0,084	0,055
	47	12	3		2,75	1,176	0,527	0,031	0,100	0,069
	48	12	4		3,70	1,258	0,731	0,029	0,118	0,089

	Point	series	Strip	Delay s	Ink transferred g/m2	Print density D	Set-off D	Show through D	Print through D	Strike through D
4 A	49	13	1	2,5	1,23	0,940	0,323	0,033	0,060	0,027
	50	13	2		1,87	1,102	0,542	0,040	0,070	0,030
	51	13	3		2,53	1,172	0,656	0,036	0,081	0,045
	52	13	4		3,34	1,285	0,873	0,035	0,085	0,050
	53	14	1	60	0,78	0,769	0,100	0,033	0,053	0,020
	54	14	2		1,63	1,048	0,296	0,033	0,062	0,029
	55	14	3		2,37	1,170	0,526	0,042	0,076	0,034
	56	14	4		3,21	1,277	0,739	0,036	0,092	0,056
4 B	57	15	1	2,5	1,34	0,935	0,331	0,040	0,060	0,020
	58	15	2		1,96	1,090	0,514	0,035	0,069	0,034
	59	15	3		2,79	1,190	0,667	0,040	0,090	0,050
	60	15	4		3,66	1,275	0,795	0,040	0,092	0,052
	61	16	1	60	1,29	0,921	0,220	0,037	0,060	0,023
	62	16	2		1,89	1,058	0,338	0,039	0,066	0,027
	63	16	3		2,75	1,189	0,496	0,040	0,081	0,041
	64	16	4		3,69	1,267	0,657	0,039	0,097	0,058
5 A	65	17	1	2,5	1,15	0,864	0,297	0,030	0,067	0,037
	66	17	2		1,84	1,027	0,431	0,032	0,077	0,045
	67	17	3		2,69	1,154	0,637	0,040	0,091	0,051
	68	17	4		3,58	1,217	0,754	0,031	0,112	0,081
	69	18	1	60	1,22	0,865	0,209	0,033	0,067	0,034
	70	18	2		1,86	1,045	0,334	0,034	0,074	0,040
	71	18	3		2,60	1,159	0,533	0,035	0,087	0,052
	72	18	4		3,64	1,244	0,628	0,037	0,110	0,073
5 B	73	19	1	2,5	1,00	0,822	0,200	0,032	0,066	0,034
	74	19	2		1,72	1,012	0,483	0,035	0,078	0,043
	75	19	3		2,53	1,147	0,636	0,034	0,091	0,057
	76	19	4		3,33	1,214	0,769	0,033	0,108	0,075
	77	20	1	60	1,24	0,904	0,211	0,030	0,069	0,039
	78	20	2		1,96	1,042	0,375	0,032	0,080	0,048
	79	20	3		2,61	1,150	0,480	0,036	0,091	0,055
	80	20	4		3,42	1,260	0,636	0,030	0,101	0,071

5.2 Set-off of different mill papers varying printing conditions - Test series 1
Printing conditions 2

	Point	series	Strip	Delay s	Ink transferred g/m^2	Print density D	Set-off D	Show through D	Print through D	Strike through D
1 A	1	1	1	2,5	1,15	0,890	0,264	0,020	0,040	0,020
	2	1	2		1,87	1,062	0,463	0,020	0,042	0,022
	3	1	3		2,59	1,194	0,578	0,021	0,050	0,029
	4	1	4		3,53	1,258	0,786	0,020	0,058	0,038
	5	2	1	60	1,31	0,939	0,155	0,020	0,042	0,022
	6	2	2		1,97	1,045	0,301	0,020	0,048	0,028
	7	2	3		2,70	1,155	0,491	0,024	0,050	0,026
	8	2	4		3,53	1,248	0,684	0,020	0,058	0,038
1 B	9	3	1	2,5	1,22	0,863	0,240	0,020	0,031	0,011
	10	3	2		1,93	1,044	0,397	0,020	0,046	0,026
	11	3	3		2,73	1,129	0,555	0,022	0,054	0,032
	12	3	4		3,87	1,213	0,693	0,021	0,072	0,051
	13	4	1	60	1,36	0,915	0,185	0,020	0,041	0,021
	14	4	2		1,98	1,008	0,284	0,026	0,048	0,022
	15	4	3		2,78	1,131	0,435	0,020	0,054	0,034
	16	4	4		3,89	1,209	0,543	0,020	0,069	0,049
2 A	17	5	1	2,5	1,15	0,865	0,128	0,023	0,051	0,028
	18	5	2		1,88	0,964	0,208	0,021	0,063	0,042
	19	5	3		2,78	1,061	0,417	0,026	0,073	0,047
	20	5	4		3,84	1,126	0,574	0,026	0,110	0,084
	21	6	1	60	1,18	0,856	0,081	0,022	0,046	0,024
	22	6	2		1,88	0,975	0,134	0,028	0,061	0,033
	23	6	3		2,84	1,068	0,228	0,020	0,071	0,051
	24	6	4		3,81	1,125	0,395	0,021	0,105	0,084
2 B	25	7	1	2,5	1,16	0,860	0,120	0,021	0,050	0,029
	26	7	2		1,79	0,968	0,251	0,025	0,057	0,032
	27	7	3		2,57	1,077	0,321	0,020	0,065	0,045
	28	7	4		3,53	1,129	0,481	0,023	0,102	0,079
	29	8	1	60	1,27	0,851	0,065	0,023	0,048	0,025
	30	8	2		1,88	0,981	0,153	0,023	0,061	0,038
	31	8	3		2,71	1,073	0,202	0,023	0,074	0,051
	32	8	4		3,47	1,132	0,320	0,024	0,090	0,066
3 A	33	9	1	2,5	1,11	0,834	0,239	0,026	0,068	0,042
	34	9	2		1,83	1,016	0,362	0,027	0,087	0,060
	35	9	3		2,55	1,123	0,523	0,030	0,100	0,070
	36	9	4		3,40	1,201	0,667	0,030	0,111	0,081
	37	10	1	60	1,32	0,873	0,144	0,025	0,068	0,043
	38	10	2		2,05	1,050	0,319	0,030	0,088	0,058
	39	10	3		2,73	1,146	0,372	0,025	0,103	0,078
	40	10	4		3,60	1,217	0,589	0,028	0,122	0,094
3 B	41	11	1	2,5	1,24	0,889	0,236	0,030	0,070	0,040
	42	11	2		1,88	1,029	0,339	0,030	0,097	0,067
	43	11	3		2,66	1,156	0,507	0,029	0,099	0,070
	44	11	4		3,51	1,229	0,633	0,030	0,121	0,091
	45	12	1	60	1,32	0,876	0,136	0,029	0,072	0,043
	46	12	2		1,98	1,049	0,312	0,031	0,080	0,049
	47	12	3		2,69	1,150	0,394	0,034	0,103	0,069
	48	12	4		3,57	1,215	0,545	0,030	0,125	0,095

Appendix 3(2) cont.

	Point	series	Strip	Delay s	Ink transferred g/m^2	Print density D	Set-off D	Show through D	Print through D	Strike through D
4 A	49	13	1	2,5	1,13	0,881	0,185	0,040	0,059	0,019
	50	13	2		1,82	1,090	0,403	0,044	0,072	0,028
	51	13	3		2,56	1,184	0,576	0,043	0,081	0,038
	52	13	4		3,20	1,255	0,755	0,040	0,091	0,051
	53	14	1	60	1,25	0,926	0,139	0,040	0,062	0,022
	54	14	2		1,86	1,097	0,283	0,043	0,066	0,023
	55	14	3		2,56	1,191	0,432	0,040	0,081	0,041
	56	14	4		3,40	1,287	0,654	0,041	0,098	0,057
4 B	57	15	1	2,5	1,28	0,928	0,238	0,031	0,059	0,028
	58	15	2		1,93	1,088	0,381	0,032	0,062	0,030
	59	15	3		2,53	1,189	0,510	0,030	0,081	0,051
	60	15	4		3,37	1,266	0,745	0,032	0,089	0,057
	61	16	1	60	1,41	0,948	0,147	0,031	0,061	0,030
	62	16	2		2,06	1,101	0,269	0,040	0,073	0,033
	63	16	3		2,80	1,224	0,420	0,035	0,078	0,043
	64	16	4		3,80	1,250	0,480	0,031	0,104	0,073
5 A	65	17	1	2,5	1,28	0,890	0,239	0,030	0,067	0,037
	66	17	2		1,95	1,050	0,372	0,031	0,075	0,044
	67	17	3		2,69	1,168	0,533	0,030	0,091	0,061
	68	17	4		3,66	1,241	0,654	0,031	0,110	0,079
	69	18	1	60	1,31	0,885	0,177	0,030	0,062	0,032
	70	18	2		1,93	1,046	0,261	0,031	0,073	0,042
	71	18	3		2,78	1,166	0,389	0,030	0,089	0,059
	72	18	4		3,71	1,249	0,574	0,035	0,109	0,074
5 B	73	19	1	2,5	1,19	0,855	0,200	0,030	0,064	0,034
	74	19	2		1,84	1,024	0,383	0,030	0,080	0,050
	75	19	3		2,65	1,151	0,587	0,030	0,088	0,058
	76	19	4		3,40	1,241	0,740	0,030	0,107	0,077
	77	20	1	60	1,38	0,890	0,149	0,030	0,064	0,034
	78	20	2		1,95	1,028	0,310	0,029	0,070	0,041
	79	20	3		2,64	1,157	0,458	0,031	0,092	0,061
	80	20	4		3,51	1,214	0,614	0,030	0,101	0,071

5.2 Set-off of different mill papers varying printing conditions - Test series 1

Printing conditions 3

Paper	Point	Series	Strip	Delay s	Ink transferred g/m^2	Print density D	Set-off D	Show through D	Print through D	Strike through D
1 A	1	1	1	0	1,19	0,895	0,454	0,020	0,038	0,018
	2	1	2		1,63	1,036	0,667	0,020	0,041	0,021
	3	1	3		2,44	1,149	0,920	0,020	0,050	0,030
	4	1	4		3,26	1,275	1,104	0,020	0,056	0,036
	5	2	1	2,5	1,19	0,919	0,421	0,018	0,040	0,022
	6	2	2		1,72	1,051	0,636	0,020	0,040	0,020
	7	2	3		2,41	1,162	0,894	0,019	0,049	0,030
	8	2	4		3,35	1,254	1,099	0,020	0,057	0,037
	9	3	1	60	1,29	0,915	0,304	0,020	0,039	0,019
	10	3	2		1,91	1,059	0,511	0,020	0,044	0,024
	11	3	3		2,65	1,178	0,776	0,020	0,049	0,029
	12	3	4		3,46	1,270	0,971	0,020	0,064	0,044
2 A	13	4	1	0	1,16	0,866	0,340	0,020	0,051	0,031
	14	4	2		1,89	0,975	0,522	0,024	0,049	0,025
	15	4	3		2,78	1,070	0,784	0,026	0,067	0,041
	16	4	4		3,83	1,137	0,995	0,027	0,088	0,061
	17	5	1	2,5	1,16	0,880	0,271	0,026	0,049	0,023
	18	5	2		1,89	0,979	0,445	0,024	0,054	0,030
	19	5	3		2,75	1,065	0,669	0,028	0,065	0,037
	20	5	4		3,79	1,129	0,914	0,025	0,092	0,067
	21	6	1	60	1,13	0,834	0,154	0,023	0,052	0,029
	22	6	2		1,83	0,972	0,295	0,023	0,051	0,028
	23	6	3		2,78	1,071	0,458	0,027	0,065	0,038
	24	6	4		3,94	1,133	0,659	0,026	0,123	0,097
3 A	25	7	1	0	1,33	0,885	0,538	0,030	0,073	0,043
	26	7	2		1,97	1,053	0,780	0,030	0,081	0,051
	27	7	3		2,65	1,152	0,938	0,029	0,101	0,072
	28	7	4		3,48	1,230	1,084	0,029	0,119	0,090
	29	8	1	2,5	1,29	0,881	0,456	0,026	0,062	0,036
	30	8	2		2,00	1,039	0,696	0,029	0,089	0,060
	31	8	3		2,69	1,150	0,903	0,030	0,099	0,069
	32	8	4		3,52	1,236	1,064	0,029	0,113	0,084
	33	9	1	60	1,31	0,896	0,306	0,027	0,072	0,045
	34	9	2		1,98	1,052	0,529	0,027	0,090	0,063
	35	9	3		2,71	1,148	0,738	0,028	0,094	0,066
	36	9	4		3,44	1,243	0,931	0,028	0,109	0,081
4 A	37	10	1	0	1,33	0,920	0,490	0,041	0,056	0,015
	38	10	2		1,88	1,096	0,779	0,041	0,064	0,023
	39	10	3		2,51	1,200	0,982	0,040	0,074	0,034
	40	10	4		3,38	1,302	1,113	0,040	0,089	0,049
	41	11	1	2,5	1,31	0,947	0,416	0,040	0,062	0,022
	42	11	2		1,88	1,097	0,685	0,040	0,061	0,021
	43	11	3		2,64	1,173	0,883	0,042	0,081	0,039
	44	11	4		3,34	1,281	1,049	0,041	0,079	0,038
	45	12	1	60	1,31	0,935	0,257	0,040	0,053	0,013
	46	12	2		1,93	1,079	0,506	0,040	0,065	0,025
	47	12	3		2,60	1,190	0,725	0,040	0,072	0,032
	48	12	4		3,37	1,272	0,960	0,040	0,082	0,042
5 A	49	13	1	0	1,24	0,860	0,478	0,030	0,067	0,037
	50	13	2		1,83	1,021	0,623	0,030	0,078	0,048
	51	13	3		2,64	1,148	0,857	0,031	0,091	0,060
	52	13	4		3,62	1,244	1,060	0,030	0,102	0,072
	53	14	1	2,5	1,16	0,873	0,414	0,030	0,064	0,034
	54	14	2		1,82	1,036	0,623	0,030	0,075	0,045
	55	14	3		2,68	1,171	0,806	0,030	0,091	0,061
	56	14	4		3,42	1,251	0,967	0,032	0,096	0,064
	57	15	1	60	1,09	0,850	0,283	0,030	0,060	0,030
	58	15	2		1,92	1,031	0,462	0,031	0,080	0,049
	59	15	3		2,71	1,156	0,668	0,032	0,091	0,059
	60	15	4		3,57	1,260	0,854	0,030	0,097	0,067

5.4 Set-off of different mill papers varying printing conditions - Test series 1

Printing conditions 4

	Point	series	Strip	Delay s	Ink transferred g/m^2	Print density D	Set-off D	Show through D	Print through D	Strike through D
1 A	1	1	1	0	1,29	0,924	0,348	0,020	0,033	0,013
	2	1	2		1,82	1,048	0,565	0,020	0,041	0,021
	3	1	3		2,56	1,170	0,810	0,020	0,051	0,031
	4	1	4		3,43	1,249	1,078	0,021	0,059	0,038
	5	2	1	2,5	1,19	0,910	0,317	0,020	0,040	0,020
	6	2	2		1,79	1,052	0,549	0,020	0,043	0,023
	7	2	3		2,84	1,205	0,852	0,020	0,055	0,035
	8	2	4		3,42	1,240	1,036	0,020	0,062	0,042
	9	3	1	60	1,16	0,908	0,224	0,020	0,040	0,020
	10	3	2		1,77	1,027	0,351	0,020	0,041	0,021
	11	3	3		2,46	1,160	0,582	0,020	0,050	0,030
	12	3	4		3,39	1,242	0,793	0,020	0,062	0,042
2 A	13	4	1	0	1,18	0,893	0,254	0,020	0,055	0,035
	14	4	2		1,93	0,977	0,382	0,020	0,060	0,040
	15	4	3		2,74	1,066	0,612	0,023	0,063	0,040
	16	4	4		3,83	1,128	0,824	0,022	0,092	0,070
	17	5	1	2,5	1,20	0,885	0,202	0,020	0,046	0,026
	18	5	2		2,00	0,962	0,313	0,022	0,062	0,040
	19	5	3		2,92	1,067	0,523	0,021	0,082	0,061
	20	5	4		3,90	1,119	0,745	0,021	0,109	0,088
	21	6	1	60	1,31	0,878	0,122	0,022	0,051	0,029
	22	6	2		2,01	0,986	0,200	0,020	0,051	0,031
	23	6	3		2,82	1,068	0,287	0,024	0,081	0,057
	24	6	4		3,69	1,132	0,454	0,022	0,096	0,074
3 A	25	7	1	0	1,22	0,895	0,382	0,030	0,071	0,041
	26	7	2		1,89	1,048	0,607	0,030	0,083	0,053
	27	7	3		2,64	1,157	0,873	0,030	0,100	0,070
	28	7	4		3,42	1,225	1,023	0,031	0,108	0,077
	29	8	1	2,5	1,28	0,896	0,321	0,030	0,071	0,041
	30	8	2		2,02	1,045	0,510	0,030	0,079	0,049
	31	8	3		2,62	1,167	0,753	0,031	0,097	0,066
	32	8	4		3,49	1,253	0,975	0,030	0,110	0,080
	33	9	1	60	1,23	0,893	0,215	0,029	0,071	0,042
	34	9	2		1,91	1,047	0,429	0,030	0,081	0,051
	35	9	3		2,66	1,150	0,604	0,031	0,101	0,070
	36	9	4		3,43	1,241	0,805	0,030	0,111	0,081
4 A	37	10	1	0	1,20	0,921	0,344	0,036	0,055	0,019
	38	10	2		1,80	1,086	0,559	0,039	0,069	0,030
	39	10	3		2,64	1,177	0,823	0,034	0,081	0,047
	40	10	4		3,40	1,297	1,062	0,038	0,087	0,049
	41	11	1	2,5	1,22	0,948	0,301	0,033	0,058	0,025
	42	11	2		1,88	1,091	0,500	0,035	0,069	0,034
	43	11	3		2,64	1,195	0,761	0,039	0,078	0,039
	44	11	4		3,35	1,283	1,013	0,038	0,092	0,054
	45	12	1	60	1,29	0,935	0,215	0,035	0,057	0,022
	46	12	2		1,93	1,099	0,402	0,036	0,064	0,028
	47	12	3		2,62	1,185	0,591	0,040	0,077	0,037
	48	12	4		3,21	1,284	0,870	0,032	0,078	0,046
5 A	49	13	1	0	1,14	0,868	0,363	0,030	0,062	0,032
	50	13	2		1,89	1,018	0,572	0,031	0,082	0,051
	51	13	3		2,68	1,146	0,814	0,031	0,094	0,063
	52	13	4		3,65	1,230	1,013	0,030	0,100	0,070
	53	14	1	2,5	1,19	0,854	0,282	0,030	0,059	0,029
	54	14	2		1,83	1,014	0,503	0,030	0,081	0,051
	55	14	3		2,68	1,152	0,719	0,031	0,094	0,063
	56	14	4		3,62	1,215	0,912	0,031	0,106	0,075
	57	15	1	60	1,10	0,835	0,186	0,030	0,056	0,026
	58	15	2		1,86	1,007	0,363	0,030	0,075	0,045
	59	15	3		2,42	1,117	0,467	0,030	0,080	0,050
	60	15	4		3,38	1,205	0,651	0,031	0,103	0,072

5.2 Set-off of different mill papers varying printing conditions - Test series 1; Printing conditions 1

Prüfbau results interpolated at constant print density 1.0 and constant ink transferred 2.0 g/m^2. R-square is for interpolation curve; x0.000 interpolated manually.

Paper	Delay s	Set-off, D 1.0	R-square	Print through 1.0	R-square	Strike through 1.0	R-square	Ink requi-rement 1.0	R-square	Print density 2.0	R-square	Set-off 2.0	R-square	Print through 2.0	R-square	Strike through 2.0
1A	2,5	0,39	0,997	0,044	0,921	0,020	0,000	1,46	0,996	1,10	0,996	0,58	0,998	0,048	0,896	0,025
	60	0,31	0,987	0,042	0,991	0,022	0,989	1,52	0,000	1,09	0,000	0,44	0,998	0,049	0,999	0,027
1B	2,5	0,46	0,999	0,046	0,972	0,024	0,957	1,79	0,992	1,03	0,992	0,54	0,996	0,048	0,993	0,026
	60	0,35	0,992	0,043	0,939	0,021	0,947	1,76	0,000	1,03	0,000	0,38	0,991	0,044	0,997	0,021
2A	2,5	0,39	0,989	0,064	0,953	0,042	0,992	2,23	0,994	0,97	0,994	0,35	0,993	0,059	0,955	0,037
	60	0,22	0,969	0,054	x0,000	0,032	0,000	2,19	0,000	0,98	0,000	0,20	0,987	0,053	0,994	0,030
2B	2,5	0,36	0,996	0,056	0,000	0,037	0,933	1,99	0,988	1,00	0,988	0,36	0,992	0,059	0,998	0,034
	60	0,18	0,983	0,055	0,946	0,033	0,969	1,90	0,000	1,01	0,000	0,20	0,994	0,054	0,988	0,033
3A	2,5	0,42	0,991	0,080	0,988	0,050	0,992	1,66	0,999	1,06	0,999	0,50	0,993	0,083	0,995	0,053
	60	0,29	0,991	0,081	0,987	0,050	0,979	1,68	0,000	1,06	0,000	0,37	0,986	0,088	0,981	0,056
3B	2,5	0,43	0,998	0,077	0,995	0,048	0,996	1,65	0,989	1,07	0,989	0,51	0,992	0,086	0,997	0,054
	60	0,30	0,984	0,079	0,970	0,048	0,983	1,70	0,000	1,06	0,000	0,36	0,999	0,085	0,995	0,055
4A	2,5	0,39	0,996	0,064	0,959	0,029	0,853	1,46	0,996	1,11	0,996	0,54	0,987	0,073	0,983	0,037
	60	0,25	0,998	0,065	0,916	0,029	0,898	1,46	0,000	1,11	0,000	0,39	0,998	0,069	0,995	0,032
4B	2,5	0,40	0,996	0,065	0,930	0,026	0,969	1,59	0,994	1,08	0,994	0,52	0,999	0,072	0,946	0,032
	60	0,28	0,999	0,064	0,948	0,026	0,939	1,62	0,000	1,07	0,000	0,35	0,999	0,069	0,996	0,030
5A	2,5	0,42	0,995	0,078	0,925	0,045	0,804	1,73	0,987	1,05	0,987	0,47	0,993	0,080	0,998	0,047
	60	0,31	0,988	0,074	0,000	0,041	0,899	1,73	0,000	1,05	0,000	0,40	0,979	0,078	0,995	0,043
5B	2,5	0,47	0,992	0,080	0,955	0,046	0,943	1,69	0,994	1,06	0,994	0,55	0,999	0,083	0,995	0,050
	60	0,32	0,996	0,077	0,998	0,045	0,983	1,68	0,000	1,06	0,000	0,36	0,994	0,081	0,996	0,049

Prüfbau results interpolated at constant print density 0.9 and constant ink transferred 1.5 g/m².

Paper	Delay s	Set-off, D 0.9	R-square	Print through 0.9	R-square	Strike through 0.9	R-square	Ink requi-rement 0.9	R-square	Print density 1.5	R-square	Set-off 1.5	R-square	Print through 1.5	R-square	Strike through 1.5
1A	2,5	0,27	0,997	0,038	0,921	0,020	0,000	1,07	0,999	1,01	0,999	0,43	0,998	0,043	0,896	0,020
	60	0,20	0,987	0,034	0,991	0,014	0,989	1,12	0,996	1,00	0,996	0,31	0,998	0,042	0,999	0,020
1B	2,5	0,36	0,999	0,041	0,972	0,019	0,957	1,28	0,986	0,95	0,986	0,42	0,996	0,043	0,993	0,021
	60	0,24	0,992	0,038	0,939	0,016	0,947	1,24	0,999	0,95	0,999	0,29	0,991	0,040	0,997	0,018
2A	2,5	0,27	0,989	0,048	0,953	0,026	0,992	1,49	0,997	0,90	0,997	0,28	0,993	0,048	0,955	0,026
	60	0,13	0,969	0,054	0,000	0,032	0,000	1,47	0,992	0,91	0,992	0,14	0,000	0,044	0,994	0,023
2B	2,5	0,24	0,996	0,056	0,000	0,026	0,933	1,35	0,986	0,93	0,986	0,27	0,992	0,050	0,998	0,026
	60	0,10	0,983	0,042	0,946	0,022	0,969	1,28	0,995	0,94	0,995	0,13	0,994	0,046	0,988	0,026
3A	2,5	0,32	0,991	0,071	0,988	0,040	0,992	1,24	1,000	0,97	1,000	0,39	0,993	0,074	0,995	0,044
	60	0,21	0,991	0,071	0,987	0,041	0,979	1,25	0,999	0,96	0,990	0,26	0,986	0,078	0,981	0,046
3B	2,5	0,34	0,998	0,067	0,995	0,038	0,996	1,26	0,995	0,96	0,995	0,40	0,992	0,074	0,997	0,043
	60	0,22	0,984	0,068	0,970	0,039	0,983	1,28	0,990	0,96	0,990	0,26	0,999	0,074	0,995	0,044
4A	2,5	0,29	0,996	0,057	0,959	0,024	0,853	1,08	0,991	1,01	0,991	0,41	0,987	0,065	0,983	0,030
	60	0,17	0,998	0,058	0,916	0,024	0,898	1,11	0,999	1,01	0,999	0,26	0,998	0,062	0,995	0,026
4B	2,5	0,31	0,996	0,056	0,930	0,018	0,969	1,18	0,992	0,98	0,992	0,38	0,999	0,063	0,946	0,024
	60	0,20	0,999	0,056	0,948	0,020	0,939	1,20	0,997	0,98	0,997	0,26	0,999	0,062	0,996	0,024
5A	2,5	0,32	0,995	0,068	0,925	0,037	0,804	1,26	0,993	0,96	0,993	0,37	0,993	0,072	0,998	0,040
	60	0,23	0,988	0,074	0,000	0,034	0,899	1,30	0,987	0,95	0,987	0,28	0,979	0,070	0,995	0,037
5B	2,5	0,34	0,992	0,071	0,955	0,038	0,943	1,25	0,996	0,96	0,996	0,42	0,999	0,074	0,995	0,041
	60	0,202	0,996	0,069	0,998	0,038	0,983	1,26	0,995	0,962	0,995	0,267	0,994	0,073	0,996	0,042

5.2 Set-off of different mill papers varying printing conditions - Test series 1; Printing conditions 2

Prüfbau results interpolated at constant print density 1.0 and constant ink transferred 2.0 g/m^2. R-square is for interpolation curve; x0.000 interpolated manually.

Paper	Delay s	Set-off, D 1.0	R-square	Print through 1.0	R-square	Strike through 1.0	R-square	Ink requi-rement 1.0	R-square	Print density 2.0	R-square	Set-off 2.0	R-square	Print through 2.0	R-square	Strike through 2.0
1A	2,5	0,37	0,979	0,043	0,000	0,022	0,000	1,57	0,982	1,08	0,982	0,46	0,990	0,045	0,968	0,024
	60	0,23	0,993	0,045	0,950	0,024	0,000	1,64	0,000	1,06	0,000	0,30	0,997	0,047	0,964	0,026
1B	2,5	0,36	0,995	0,042	0,988	0,020	0,990	1,82	0,985	1,03	0,985	0,40	0,988	0,045	0,989	0,023
	60	0,27	0,997	0,047	0,949	0,024	0,925	1,86	0,000	1,02	0,000	0,29	0,986	0,047	0,993	0,025
2A	2,5	0,27	0,994	0,071	0,906	0,046	0,900	2,15	0,997	0,98	0,997	0,25	0,985	0,064	0,974	0,040
	60	0,17	0,971	0,067	0,920	0,042	0,939	2,16	0,000	0,98	0,000	0,15	0,986	0,060	0,972	0,035
2B	2,5	0,26	0,962	0,064	0,000	0,036	0,000	2,01	0,987	1,00	0,987	0,26	0,983	0,061	0,940	0,038
	60	0,16	0,982	0,065	0,985	0,041	0,996	2,11	0,000	0,99	0,000	0,15	0,969	0,062	0,996	0,039
3A	2,5	0,37	0,990	0,086	0,998	0,058	0,998	1,80	0,992	1,04	0,992	0,41	0,997	0,090	1,000	0,062
	60	0,24	0,973	0,083	0,989	0,056	0,980	1,83	0,000	1,03	0,000	0,28	0,971	0,087	1,000	0,059
3B	2,5	0,32	0,998	0,086	0,911	0,055	0,919	1,72	0,987	1,05	0,987	0,37	0,995	0,093	0,922	0,063
	60	0,24	0,989	0,082	0,000	0,048	0,000	1,83	0,000	1,03	0,000	0,28	0,978	0,084	0,983	0,053
4A	2,5	0,29	1,000	0,067	0,986	0,025	0,944	1,52	0,990	1,10	0,990	0,42	0,989	0,074	0,996	0,032
	60	0,19	1,000	0,064	0,000	0,023	0,825	1,50	0,000	1,10	0,000	0,30	0,995	0,071	0,979	0,029
4B	2,5	0,29	0,986	0,062	0,000	0,030	0,000	1,54	0,963	1,09	0,963	0,40	0,995	0,068	0,920	0,037
	60	0,18	0,999	0,065	0,000	0,030	0,000	1,60	0,000	1,08	0,000	0,27	0,980	0,069	0,967	0,035
5A	2,5	0,33	0,996	0,074	0,000	0,044	0,938	1,72	0,992	1,05	0,992	0,41	0,992	0,079	0,991	0,048
	60	0,24	0,980	0,071	0,964	0,040	0,984	1,76	0,000	1,04	0,000	0,28	0,992	0,074	0,999	0,042
5B	2,5	0,36	0,999	0,077	0,972	0,046	0,979	1,75	0,988	1,05	0,988	0,42	0,998	0,080	0,973	0,050
	60	0,26	0,991	0,072	0,947	0,042	0,969	1,83	0,000	1,03	0,000	0,33	0,999	0,075	0,950	0,045

Prüfbau results interpolated at constant print density 0.9 and constant ink transferred 1.5 g/m².

Paper	Delay s	Set-off, D 0.9	R-square	Print through 0.9	R-square	Strike through 0.9	R-square	Ink requi-rement 0.9	R-square	Print density 1.5	R-square	Set-off 1.5	R-square	Print through 1.5	R-square	Strike through 1.5
1A	2,5	0,27	0,979	0,043	0,000	0,022	0,000	1,17	0,988	0,99	0,988	0,35	0,990	0,041	0,968	0,021
	60	0,13	0,993	0,041	0,950	0,024	0,000	1,19	0,994	0,97	0,994	0,19	0,997	0,044	0,964	0,023
1B	2,5	0,26	0,995	0,033	0,988	0,013	0,990	1,31	0,983	0,94	0,983	0,30	0,988	0,037	0,989	0,016
	60	0,18	0,997	0,040	0,949	0,018	0,925	1,31	0,992	0,94	0,992	0,21	0,986	0,043	0,993	0,021
2A	2,5	0,15	0,994	0,054	0,906	0,031	0,900	1,36	0,998	0,92	0,998	0,17	0,985	0,055	0,974	0,033
	60	0,10	0,971	0,050	0,920	0,027	0,939	1,40	0,997	0,92	0,997	0,11	0,986	0,051	0,972	0,028
2B	2,5	0,16	0,962	0,064	0,000	0,036	0,000	1,35	0,991	0,93	0,991	0,18	0,983	0,053	0,940	0,031
	60	0,09	0,982	0,052	0,985	0,029	0,996	1,47	0,994	0,91	0,994	0,09	0,969	0,053	0,996	0,030
3A	2,5	0,28	0,990	0,075	0,998	0,048	0,998	1,33	0,996	0,94	0,996	0,31	0,997	0,079	1,000	0,052
	60	0,16	0,973	0,070	0,989	0,044	0,980	1,38	0,991	0,93	0,991	0,18	0,971	0,073	1,000	0,047
3B	2,5	0,24	0,998	0,073	0,911	0,043	0,919	1,28	0,997	0,95	0,997	0,28	0,995	0,080	0,922	0,051
	60	0,16	0,989	0,082	0,000	0,048	0,000	1,38	0,984	0,94	0,984	0,19	0,978	0,074	0,983	0,044
4A	2,5	0,20	1,000	0,059	0,986	0,019	0,944	1,15	0,988	1,00	0,988	0,29	0,989	0,066	0,996	0,024
	60	0,12	1,000	0,064	0,000	0,018	0,825	1,13	0,992	1,00	0,992	0,19	0,995	0,064	0,979	0,023
4B	2,5	0,21	0,986	0,062	0,000	0,030	0,000	1,16	0,994	0,99	0,994	0,28	0,995	0,060	0,920	0,029
	60	0,12	0,999	0,065	0,000	0,030	0,000	1,19	0,947	0,99	0,947	0,17	0,980	0,062	0,967	0,029
5A	2,5	0,24	0,996	0,074	0,000	0,036	0,938	1,28	0,991	0,95	0,991	0,29	0,992	0,069	0,991	0,039
	60	0,18	0,980	0,061	0,964	0,032	0,984	1,33	0,994	0,94	0,994	0,20	0,992	0,065	0,999	0,036
5B	2,5	0,26	0,999	0,068	0,972	0,037	0,979	1,33	0,999	0,94	0,999	0,31	0,998	0,071	0,973	0,041
	60	0,16	0,991	0,062	0,947	0,033	0,969	1,39	0,981	0,93	0,981	0,18	0,999	0,065	0,950	0,036

5.2 Set-off of different mill papers varying printing conditions - Test series 1; Printing conditions 3

Prüfbau results interpolated at constant print density 1.0 and constant ink transferred 2.0 g/m^2. R-square is for interpolation curve; x0.000 interpolated manually.

Paper	Delay s	Set-off, D 1.0	R-square	Print through 1.0	R-square	Strike through 1.0	R-square	Ink requi-rement 1.0	R-square	Print density 2.0	R-square	Set-off 2.0	R-square	Print through 2.0	R-square	Strike through 2.0
1A	0	0,63	0,993	0,042	0,959	0,021	0,963	1,55	0,991	1,09	0,991	0,79	1,000	0,046	0,987	0,025
	2,5	0,55	0,999	0,042	0,824	0,023	0,000	1,49	0,997	0,94	0,989	0,76	0,998	0,045	0,947	0,026
	60	0,42	0,999	0,042	0,876	0,022	0,930	1,64	1,000	1,07	1,000	0,53	0,992	0,045	0,967	0,024
2A	0	0,58	0,999	0,060	0,789	0,038	x0,000	2,09	0,999	0,99	0,999	0,56	0,997	0,056	0,899	0,033
	2,5	0,49	1,000	0,061	0,876	0,034	0,893	2,07	0,999	0,99	0,999	0,48	1,000	0,057	0,965	0,031
	60	0,34	0,998	0,062	0,000	0,035	0,000	2,15	0,991	0,98	0,991	0,31	0,996	0,059	0,867	0,035
3A	0	0,70	1,000	0,082	0,917	0,052	0,928	1,79	0,991	1,04	0,980	0,78	0,998	0,084	0,986	0,054
	2,5	0,63	1,000	0,081	0,991	0,053	0,986	1,79	0,999	1,04	0,999	0,68	0,991	0,085	0,987	0,057
	60	0,45	0,999	0,083	0,975	0,055	0,968	1,75	0,998	1,05	0,998	0,51	0,995	0,087	0,958	0,059
4A	0	0,61	0,991	0,060	0,934	0,018	0,988	1,57	0,990	1,10	0,990	0,79	0,982	0,066	0,999	0,026
	2,5	0,51	0,993	0,063	0,000	0,023	0,000	1,50	0,986	1,10	0,986	0,71	0,998	0,067	0,000	0,026
	60	0,34	0,991	0,058	0,992	0,018	0,988	1,56	0,999	1,09	0,999	0,51	0,996	0,065	0,994	0,023
5A	0	0,62	0,991	0,078	0,996	0,047	0,999	1,79	0,995	1,04	0,995	0,67	0,995	0,082	0,997	0,052
	2,5	0,57	0,999	0,074	0,990	0,043	0,985	1,66	1,000	1,07	1,000	0,65	0,994	0,079	0,989	0,048
	60	0,43	0,999	0,076	0,995	0,046	0,999	1,77	1,000	1,05	0,998	0,49	0,999	0,080	0,993	0,049

Prüfbau results interpolated at constant print density 0.9 and constant ink transferred 1.5 g/m².

Paper	Delay s	Set-off, D 0.9	R-square	Print through 0.9	R-square	Strike through 0.9	R-square	Ink requi-rement 0.9	R-square	Print density 1.5	R-square	Set-off 1.5	R-square	Print through 1.5	R-square	Strike through 1.5
1A	0	0,46	0,993	0,037	0,959	0,018	0,963	1,18	0,991	0,99	0,991	0,61	1,000	0,041	0,987	0,021
	2,5	0,39	0,999	0,037	0,824	0,023	0,000	1,10	0,997	0,84	0,989	0,57	0,998	0,041	0,947	0,022
	60	0,29	0,999	0,037	0,876	0,017	0,930	1,25	1,000	0,97	1,000	0,37	0,992	0,040	0,967	0,020
2A	0	0,39	0,999	0,049	0,789	0,038	0,000	1,35	0,999	0,92	0,999	0,43	0,997	0,050	0,899	0,028
	2,5	0,30	1,000	0,048	0,876	0,023	0,893	1,29	0,999	0,93	0,999	0,35	1,000	0,051	0,965	0,025
	60	0,21	0,998	0,062	0,000	0,035	0,000	1,35	0,991	0,91	0,991	0,22	0,996	0,051	0,867	0,028
3A	0	0,56	1,000	0,071	0,917	0,042	0,928	1,35	0,991	0,94	0,980	0,61	0,998	0,075	0,986	0,045
	2,5	0,48	1,000	0,066	0,991	0,039	0,986	1,35	0,999	0,94	0,999	0,53	0,991	0,071	0,987	0,044
	60	0,31	0,999	0,073	0,975	0,046	0,968	1,32	0,998	0,95	0,998	0,37	0,995	0,077	0,958	0,050
4A	0	0,47	0,991	0,053	0,934	0,013	0,988	1,23	0,990	0,98	0,990	0,60	0,982	0,058	0,999	0,017
	2,5	0,32	0,993	0,063	0,000	0,023	0,000	1,12	0,986	1,00	0,986	0,52	0,998	0,067	0,000	0,022
	60	0,23	0,991	0,050	0,992	0,010	0,988	1,18	0,999	0,99	0,999	0,34	0,996	0,057	0,994	0,016
5A	0	0,51	0,991	0,069	0,996	0,039	0,999	1,35	0,995	0,94	0,995	0,55	0,995	0,073	0,997	0,042
	2,5	0,45	0,999	0,066	0,990	0,036	0,985	1,25	1,000	0,96	1,000	0,52	0,994	0,071	0,989	0,040
	60	0,32	0,999	0,066	0,995	0,036	0,999	1,29	1,000	0,96	0,998	0,38	0,999	0,071	0,993	0,040

5.2 Set-off of different mill papers varying printing conditions - Test series 1; Printing conditions 4

Prüfbau results interpolated at constant print density 1.0 and constant ink transferred 2.0 g/m^2. R-square is for interpolation curve; x0.000 interpolated manually.

Paper	Delay s	Set-off, D 1.0	R-square	Print through 1.0	R-square	Strike through 1.0	R-square	Ink requi- rement 1.0	R-square	Print density 2.0	R-square	Set-off 2.0	R-square	Print through 2.0	R-square	Strike through 2.0
1A	0	0,46	0,997	0,038	0,992	0,018	0,999	1,59	0,996	1,08	0,996	0,61	0,996	0,044	0,998	0,024
	3	0,44	0,994	0,043	0,922	0,023	0,937	1,55	0,995	1,08	0,995	0,58	0,993	0,046	0,989	0,026
	60	0,32	1,000	0,043	x0,000	0,022	0,900	1,57	0,994	1,08	0,994	0,43	0,993	0,046	0,956	0,025
2A	0	0,44	0,998	0,064	0,000	0,043	0,000	2,05	0,994	1,00	0,994	0,42	0,992	0,061	0,880	0,040
	2,5	0,38	0,997	0,069	0,985	0,047	0,991	2,24	0,989	0,98	0,989	0,34	0,991	0,063	0,995	0,042
	60	0,22	0,981	0,067	0,000	0,042	0,879	2,13	1,000	0,98	1,000	0,19	0,992	0,060	0,914	0,038
3A	0	0,53	0,998	0,080	0,988	0,050	0,991	1,65	0,997	1,06	0,997	0,63	0,991	0,087	0,988	0,056
	2,5	0,44	1,000	0,079	0,967	0,048	0,975	1,76	0,994	1,05	0,994	0,53	0,993	0,083	0,971	0,053
	60	0,33	0,992	0,080	0,967	0,050	0,969	1,68	0,999	1,06	0,999	0,43	0,996	0,085	0,982	0,055
4A	0	0,44	0,989	0,063	0,983	0,025	0,939	1,50	0,987	1,10	0,987	0,61	0,999	0,071	0,995	0,035
	2,5	0,36	0,999	0,062	0,989	0,028	0,969	1,42	0,999	1,11	0,999	0,55	0,999	0,069	0,993	0,033
	60	0,28	0,999	0,061	0,915	0,024	0,975	1,53	0,993	1,10	0,993	0,41	0,996	0,067	0,956	0,030
5A	0	0,54	0,999	0,076	0,965	0,046	0,978	1,75	0,997	1,04	0,997	0,60	0,992	0,082	0,983	0,052
	2,5	0,47	0,997	0,077	0,991	0,045	0,981	1,80	0,989	1,04	0,989	0,56	0,998	0,082	0,992	0,052
	60	0,33	0,991	0,072	0,956	0,041	0,966	1,78	0,995	1,04	0,995	0,38	0,997	0,075	0,982	0,045

Prüfbau results interpolated at constant print density 0.9 and constant ink transferred 1.5 g/m².

Paper	Delay s	Set-off, D 0.9	R-square	Print through 0.9	R-square	Strike through 0.9	R-square	Ink requi- rement 0.9	R-square	Print density 1.5	R-square	Set-off 1.5	R-square	Print through 1.5	R-square	Strike through 1.5
1A	0	0,33	0,997	0,030	0,992	0,012	0,999	1,18	0,996	0,98	0,996	0,44	0,996	0,037	0,998	0,017
	2,5	0,31	0,994	0,038	0,922	0,018	0,937	1,14	0,995	0,99	0,995	0,42	0,993	0,042	0,989	0,022
	60	0,22	1,000	0,043	0,000	0,018	0,900	1,15	0,994	0,99	0,994	0,30	0,993	0,041	0,956	0,021
2A	0	0,26	0,998	0,064	0,000	0,043	0,000	1,26	0,994	0,94	0,994	0,31	0,992	0,056	0,880	0,035
	2,5	0,22	0,997	0,049	0,985	0,028	0,991	1,35	0,989	0,92	0,989	0,24	0,991	0,051	0,995	0,031
	60	0,13	0,981	0,067	0,000	0,028	0,879	1,42	1,000	0,91	1,000	0,14	0,992	0,050	0,914	0,028
3A	0	0,39	0,998	0,070	0,988	0,041	0,991	1,21	0,997	0,97	0,997	0,48	0,991	0,077	0,988	0,047
	2,5	0,32	1,000	0,069	0,967	0,040	0,975	1,30	0,994	0,95	0,994	0,38	0,993	0,073	0,971	0,043
	60	0,23	0,992	0,070	0,967	0,041	0,969	1,25	0,999	0,96	0,999	0,30	0,996	0,076	0,982	0,046
4A	0	0,32	0,989	0,053	0,983	0,018	0,939	1,12	0,987	1,00	0,987	0,45	0,999	0,063	0,995	0,026
	2,5	0,25	0,999	0,054	0,989	0,022	0,969	1,05	0,999	1,02	0,999	0,39	0,999	0,062	0,993	0,028
	60	0,19	0,999	0,054	0,915	0,020	0,975	1,17	0,993	0,99	0,993	0,27	0,996	0,060	0,956	0,024
5A	0	0,40	0,999	0,067	0,965	0,036	0,978	1,28	0,997	0,95	0,997	0,47	0,992	0,073	0,983	0,042
	2,5	0,34	0,997	0,065	0,991	0,034	0,981	1,34	0,989	0,94	0,989	0,40	0,998	0,070	0,992	0,040
	60	0,24	0,991	0,062	0,956	0,031	0,966	1,33	0,995	0,94	0,995	0,28	0,997	0,065	0,982	0,035

5.2.4 The order of the magnitude of the set-off parameters, Taguchi analysis

Table A. Taguchi L_8 array for analysing parameters of set-off. Interaction of variables 1 and 2 affects on variable 3 and variables 1 and 4 on variable 5.

Design Summary, set-off and strike through (ST) of papers 2 and 5												
Variables	1	1	2	3	4	5	6	7	Dependent variables			
	Ink g/m^2	PD	Counter Paper	PD x Count p.	Paper	PD x Paper	Set-off pressure	Delay s	Set-off ink	Set-off D	ST ink	ST D
1	1,50	0.9	own	1	dip	1	10kN	2.5s	0,17	0,15	0,033	0,031
2	1,50	0.9	own	1	virgin	2	20kN	60s	0,28	0,23	0,037	0,034
3	1,50	0.9	coat	2	dip	1	20kN	60s	0,22	0,21	0,028	0,035
4	1,50	0.9	coat	2	virgin	2	10kN	2.5s	0,40	0,34	0,040	0,034
5	2.0	1.0	own	2	dip	2	10kN	60s	0,16	0,17	0,035	0,042
6	2.0	1.0	own	2	virgin	1	20kN	2.5s	0,47	0,42	0,047	0,045
7	2.0	1.0	coat	1	dip	2	20kN	2.5s	0,48	0,49	0,031	0,034
8	2.0	1.0	coat	1	virgin	1	10kN	60s	0,39	0,33	0,045	0,041

Table B. The parameter values for levels 1 and 2, and explanation for the dependent values.

Variable	**Parameters for Taguchi analysis**	**Level 1**	**Level 2**
1	Constant ink amount g/m^2	1.5	2.0
1	Constant print density PD	0.9	1.0
2	Counter paper	own	coated
3	Interaction 1 and 2		
4	Paper	DIP	virgin pulp
5	Interaction 1 and 4		
6	Set-off pressure kN/m	10	20
7	Set-off delay time s	2.5	60

Dependent variables	
Set-off ink	Set-off at a constant ink transferred
Set-off D	Set-off at a constant print density
ST ink	Strike through at a constant ink transferred
ST D	Strike through at a constant print density

Test series 1. Average values of Prüfbau printing results. Paper samples 1-5, A side N = 10; B side N = 5.

Paper	Ink requirement 1.0 D	Print through 1.0 D	Strike through 1.0 D	Print density 2.0 g/m^2	Print through 2.0 g/m^2	Strike through 2.0 g/m^2	Ink requirement 0.9 D	Print through 0.9 D	Strike through 0.9 D	Print density 1.5 g/m^2	Print through 1.5 g/m^2	Strike through 1.5 g/m^2
Average 1A	1,56	0,042	0,022	1,07	0,046	0,025	1,15	0,038	0,019	0,97	0,041	0,021
STD.dev.	0,058	0,002	0,002	0,045	0,001	0,001	0,051	0,004	0,004	0,046	0,002	0,002
Average 1B	1,81	0,045	0,022	1,03	0,046	0,024	1,29	0,038	0,017	0,95	0,041	0,019
STD.dev.	0,041	0,002	0,002	0,006	0,002	0,002	0,035	0,003	0,003	0,006	0,003	0,003
Average 2A	2,14	0,064	0,040	0,98	0,059	0,036	1,37	0,054	0,031	0,92	0,051	0,029
STD.dev.	0,064	0,005	0,005	0,007	0,003	0,004	0,073	0,007	0,006	0,011	0,003	0,004
Average 2B	2,00	0,060	0,037	1,00	0,059	0,036	1,36	0,054	0,028	0,92	0,050	0,028
STD.dev.	0,083	0,005	0,003	0,011	0,003	0,003	0,079	0,009	0,006	0,014	0,003	0,003
Average 3A	1,74	0,081	0,052	1,05	0,086	0,056	1,30	0,071	0,042	0,95	0,075	0,047
STD.dev.	0,066	0,002	0,003	0,013	0,002	0,003	0,057	0,002	0,003	0,014	0,002	0,003
Average 3B	1,73	0,081	0,050	1,05	0,087	0,056	1,30	0,073	0,042	0,95	0,075	0,045
STD.dev.	0,079	0,004	0,004	0,015	0,004	0,005	0,053	0,007	0,005	0,012	0,003	0,003
Average 4A	1,50	0,063	0,024	1,10	0,069	0,030	1,13	0,057	0,019	1,00	0,062	0,024
STD.dev.	0,046	0,002	0,004	0,006	0,003	0,004	0,051	0,005	0,005	0,011	0,003	0,004
Average 4B	1,59	0,064	0,028	1,08	0,070	0,033	1,18	0,060	0,025	0,98	0,062	0,027
STD.dev.	0,034	0,001	0,002	0,009	0,002	0,003	0,016	0,004	0,006	0,007	0,001	0,003
Average 5A	1,75	0,075	0,044	1,05	0,079	0,048	1,30	0,067	0,035	0,95	0,070	0,039
STD.dev.	0,042	0,002	0,002	0,009	0,003	0,004	0,034	0,004	0,002	0,009	0,003	0,003
Average 5B	1,74	0,076	0,045	1,05	0,080	0,048	1,31	0,067	0,037	0,95	0,071	0,040
STD.dev.	0,070	0,003	0,002	0,013	0,004	0,002	0,065	0,004	0,002	0,016	0,004	0,003

5.2.6 Paper properties vs. set-off, Test series 1. Variable specifications of the correlation tables in Appendix 6(3-5).

Short name	Specification	Short name	Specification
GRAMMAGE	Grammage of paper, g/m^2	2 SO6_9	Set-off 60 s at a given density 0.9, printing conditions 2
THICKNES	Thickness of paper, µm	3 SO0_9	Set-off 0 s at a given density 0.9, printing conditions 3
BULK	Bulk of paper cm^3/g	3 SO25_9	Set-off 2,5 s at a given density 0.9, printing conditions 3
ASH550°C	Ash of paper measured using T=550 °C	3 SO6_9	Set-off 60 s at a given density 0.9, printing conditions 3
ASH925°C	Ash of paper measured using T=925 °C	4 SO0_9	Set-off 0 s at a given density 0.9, printing conditions 4
EMCO_S	Emco DPM S parameter	4 SO25_9	Set-off 2,5 s at a given density 0.9, printing conditions 4
FORMATIO	Formation of paper	4 SO6_9	Set-off 60 s at a given density 0.9, printing conditions 4
BENDTSEN	Bendtsen roughness, ml/min	1 SO2510	Set-off 2,5 s at a given density 1, printing conditions 1
PERMEABI	Bendtsen porosity, ml/min	1 SO610	Set-off 60 s at a given density 1, printing conditions 1
PPS_5	PPS 5, roughness, µm	2 SO2510	Set-off 2,5 s at a given density 1, printing conditions 2
PPS_10	PPS 10, roughness, µm	2 SO610	Set-off 60 s at a given density 1, printing conditions 2
PPS_20	PPS 20, roughness, µm	3 SO0_10	Set-off 0 s at a given density 1, printing conditions 3
PPSCOMP5	Compressibility of paper as a ratio of PPS 5 and PPS 10	3 SO2510	Set-off 2,5 s at a given density 1, printing conditions 3
PPSCOM10	Compressibility of paper as a ratio of PPS 10 and PPS 20	3 SO610	Set-off 60 s at a given density 1, printing conditions 3
PPSCOM52	Compressibility of paper as a ratio of PPS 5 and PPS 20	4 SO0_10	Set-off 0 s at a given density 1, printing conditions 4
UNGER	Unger absorption, g/m^2	4 SO2510	Set-off 2,5 s at a given density 1, printing conditions 4
BRIGHTNE	ISO brightness of paper , %	4 SO610	Set-off 60 s at a given density 1, printing conditions 4
Y_VALUE	Y value of paper, %	1SO25I15	Set-off 2,5 s at a given ink weight 1.5 g/m^2, printing conditions 1
OPACITY	Opacity of paper, %	1SO6_I15	Set-off 60 s at a given ink weight 1.5 g/m^2, printing conditions 1
L_SCAT	Light scatter coefficient, m^2/kg	2SO25I15	Set-off 2,5 s at a given ink weight 1.5 g/m^2, printing conditions 2
L_	L* value	2SO6_I15	Set-off 60 s at a given ink weight 1.5 g/m^2, printing conditions 2
A_	a* value	3SO0_I15	Set-off 0 s at a given ink weight 1.5 g/m^2, printing conditions 3
B_	b* value	3SO25I15	Set-off 2,5 s at a given ink weight 1.5 g/m^2, printing conditions 3
INKD09AV	Average of ink requirement at print density 0.9	3SO6_I15	Set-off 60 s at a given ink weight 1.5 g/m^2, printing conditions 3
INKD10AV	Average of ink requirement at print density 1.0	4SO0_I15	Set-off 0 s at a given ink weight 1.5 g/m^2, printing conditions 4
PTD09AV	Average of print through at print density 0.9	4SO25I15	Set-off 2,5 s at a given ink weight 1.5 g/m^2, printing conditions 4
PTD10AV	Average of print through at print density 1.0	4SO6_I15	Set-off 60 s at a given ink weight 1.5 g/m^2, printing conditions 4
STRD09AV	Average of strike through at print density 0.9	1SO25_I2	Set-off 2,5 s at a given ink weight 2 g/m^2, printing conditions 1
STRD10AV	Average of strike through at print density 1.0	1 SO6_I2	Set-off 60 s at a given ink weight 2 g/m^2, printing conditions 1
PD_I15AV	Average of print density at the constant ink amount 1.5 g/m2	2SO25_I2	Set-off 2,5 s at a given ink weight 2 g/m^2, printing conditions 2
PD_I20AV	Average of print density at the constant ink amount 2.0 g/m2	2 SO6_I2	Set-off 60 s at a given ink weight 2 g/m^2, printing conditions 2
PT_I15AV	Average of print through at the constant ink amount 1.5 g/m2	3 SO0_I2	Set-off 0 s at a given ink weight 2 g/m^2, printing conditions 3
PT_I20AV	Average of print through at the constant ink amount 2.0 g/m2	3SO25_I2	Set-off 2,5 s at a given ink weight 2 g/m^2, printing conditions 3
STR_I15A	Average of strike through at the constant ink amount 1.5 g/m2	3SO6_I2	Set-off 60 s at a given ink weight 2 g/m^2, printing conditions 3
STR_I20A	Average of strike through at the constant ink amount 2.0 g/m2	4SO0_I2	Set-off 0 s at a given ink weight 2 g/m^2, printing conditions 4
1 SO25_9	Set-off 2,5 s at a given density 0.9, printing conditions 1	4SO25_I2	Set-off 2,5 s at a given ink weight 2 g/m^2, printing conditions 4
1 SO6_9	Set-off 60 s at a given density 0.9, printing conditions 1	4SO6_I2	Set-off 60 s at a given ink weight 2 g/m^2, printing conditions 4
2 SO25_9	Set-off 2,5 s at a given density 0.9, printing conditions 2		

5.2.6 Paper properties vs. set-off, Test series 1

Marked correlations are significant at p < ,05000 ; N = 10, |r| ≧ 0,63 and N = 5, |r| ≧ 0,88

	N	GRAMMAGE	THICKNES	BULK	ASH550°C	ASH925°C	EMCO_S	FORMATIO	BENDTSEN	PERMEABI	PPS_5	PPS_10	PPS_20
GRAMMAGE	10	1	,883*	0,294	-0,234	-0,225	-0,47	,737*	0,286	-0,591	0,304	-0,089	0,152
THICKNES	10	,883*	1	,707*	-0,549	-0,542	-0,587	0,358	0,164	-0,234	0,126	-0,298	-0,128
BULK	10	0,294	,707*	1	-,799*	-,797*	-0,491	-0,379	-0,152	0,427	-0,251	-0,518	-0,524
ASH550°C	10	-0,234	-0,549	-,799*	1	1,000*	,715*	0,198	,661*	-0,256	,722*	,925*	,889*
ASH925°C	10	-0,225	-0,542	-,797*	1,000*	1	,710*	0,205	,667*	-0,264	,728*	,928*	,892*
EMCO_S	10	-0,47	-0,587	-0,49	,715*	,710*	1	-0,327	0,299	0,411	0,349	,652*	,634*
FORMATIO	10	,737*	0,358	-0,38	0,198	0,205	-0,327	1	0,253	-,946*	0,328	0,117	0,324
BENDTSEN	10	0,286	0,164	-0,15	,661*	,667*	0,299	0,253	1	-0,311	,992*	,878*	,864*
PERMEABI	10	-0,591	-0,234	0,427	-0,256	-0,264	0,411	-,946*	-0,311	1	-0,366	-0,18	-0,299
PPS_5	10	0,304	0,126	-0,25	,722*	,728*	0,349	0,328	,992*	-0,366	1	,904*	,915*
PPS_10	10	-0,089	-0,298	-0,52	,925*	,928*	,652*	0,117	,878*	-0,18	,904*	1	,950*
PPS_20	10	0,152	-0,128	-0,52	,889*	,892*	,634*	0,324	,864*	-0,299	,915*	,950*	1
PPSCOMP5	10	,785*	,900*	,666*	-,767*	-,761*	-,838*	0,393	-0,204	-0,307	-0,237	-0,628	-0,475
PPSCOM10	10	-,741*	-0,495	0,075	0,017	0,014	-0,042	-,646*	-0,035	0,365	-0,12	0,056	-0,258
PPSCOM52	10	0,08	0,409	,697*	-,705*	-,702*	-,824*	-0,207	-0,217	0,038	-0,324	-0,538	-,673*
UNGER	10	-0,345	0,008	0,571	-0,558	-0,564	0,168	-,780*	-0,563	,913*	-0,606	-0,511	-0,536
BRIGHTNE	10	,815*	0,603	0,038	-0,286	-0,282	-0,336	,742*	-0,174	-0,512	-0,104	-0,348	-0,047
Y_VALUE	10	,857*	,682*	0,134	-0,358	-0,353	-0,418	,728*	-0,164	-0,508	-0,106	-0,387	-0,093
OPACITY	10	0,025	-0,013	-0,13	,636*	,641*	0,257	0,035	,940*	-0,19	,903*	,853*	,733*
L_SCAT	10	0,567	0,241	-0,4	,634*	,642*	0,094	,739*	,833*	-,745*	,878*	,714*	,821*
L_	10	,878*	,690*	0,114	-0,334	-0,328	-0,449	,770*	-0,123	-0,568	-0,067	-0,358	-0,07
A_	10	-0,116	0,231	0,6	-0,063	-0,062	0,025	-0,569	0,484	0,455	0,373	0,274	0,099
B_	10	-0,341	0,083	,657*	-0,467	-0,467	-0,376	-,665*	-0,09	0,471	-0,214	-0,263	-0,502
INKD09AV	10	-,728*	-,670*	-0,3	0,566	0,562	0,61	-0,556	0,324	0,403	0,299	0,58	0,357
INKD10AV	10	-0,51	-0,621	-0,54	,829*	,827*	,713*	-0,23	0,565	0,114	0,576	,824*	,677*
PTD09AV	10	-,813*	-,642*	-0,05	-0,278	-0,287	0,094	-,649*	-,783*	0,583	-,797*	-0,486	-,641*
PTD10AV	10	-,853*	-,670*	-0,06	-0,239	-0,248	0,112	-,686*	-,730*	0,598	-,750*	-0,432	-0,611
STRD09AV	10	-,920*	-,696*	-0,03	-0,087	-0,095	0,139	-,769*	-0,449	0,592	-0,498	-0,192	-0,452
STRD10AV	10	-,950*	-,737*	-0,07	-0,008	-0,016	0,212	-,784*	-0,385	0,603	-0,432	-0,109	-0,376
PD_I15AV	10	0,583	0,554	0,296	-,672*	-,670*	-0,601	0,44	-0,558	-0,275	-0,529	-,747*	-0,534
PD_I20AV	10	0,449	0,524	0,437	-,807*	-,806*	-,651*	0,237	-,667*	-0,101	-,663*	-,861*	-,700*
PT_I15AV	10	-,686*	-0,47	0,111	-0,477	-0,485	-0,093	-0,612	-,874*	0,561	-,898*	-,660*	-,793*
PT_I20AV	10	-,730*	-0,524	0,066	-0,423	-0,431	-0,063	-0,623	-,844*	0,555	-,868*	-0,611	-,760*
STR_I15A	10	-,850*	-0,579	0,11	-0,278	-0,285	-0,01	-,772*	-0,578	0,611	-,635*	-0,374	-0,618
STR_I20A	10	-,867*	-0,612	0,067	-0,248	-0,255	0,012	-,759*	-0,581	0,597	-,633*	-0,359	-0,602
1 SO25_9	10	-0,025	0,299	,658*	-,727*	-,727*	-0,519	-0,363	-0,441	0,328	-0,517	-0,63	-,696*
1 SO6_9	10	0,271	0,614	,852*	-,863*	-,861*	-,703*	-0,213	-0,349	0,211	-0,435	-,686*	-,698*
2 SO25_9	10	0,216	0,599	,890*	-,811*	-,808*	-,717*	-0,283	-0,219	0,223	-0,325	-0,583	-,650*
2 SO6_9	10	0,007	0,425	,856*	-,785*	-,785*	-0,523	-0,489	-0,329	0,451	-0,432	-0,592	-,680*
3 SO0_9	5	-0,268	0,063	0,553	-0,826	-0,828	-0,634	-0,44	-0,743	0,341	-0,818	-0,84	-,964*
3 SO25_9	5	-0,347	0,083	0,682	-0,649	-0,651	-0,482	-0,654	-0,357	0,491	-0,473	-0,511	-0,722
3 SO6_9	5	0,459	0,665	0,705	-0,738	-0,738	-0,24	-0,098	-0,414	0,35	-0,428	-0,632	-0,446
4 SO0_9	5	-0,281	0,147	0,744	-0,844	-0,847	-0,435	-0,665	-0,655	0,63	-0,745	-0,769	-,886*
4 SO25_9	5	-0,061	0,398	,899*	-0,781	-0,78	-0,534	-0,574	-0,287	0,498	-0,405	-0,56	-0,69
4 SO6_9	5	0,043	0,474	,907*	-,902*	-,902*	-0,636	-0,462	-0,438	0,429	-0,542	-0,724	-0,801
1 SO2510	10	-0,053	0,31	,711*	-0,605	-0,605	-0,353	-0,48	-0,233	0,447	-0,321	-0,432	-0,52
1 SO610	10	0,32	,692*	,928*	-,822*	-,819*	-,664*	-0,245	-0,198	0,242	-0,296	-0,58	-0,599
2 SO2510	10	0,222	0,6	,873*	-,683*	-,679*	-0,617	-0,297	-0,039	0,228	-0,149	-0,411	-0,49
2 SO610	10	0,054	0,482	,890*	-,711*	-,709*	-0,529	-0,475	-0,144	0,406	-0,26	-0,457	-0,566
3 SO0_10	5	-0,224	0,049	0,433	-0,637	-0,637	-0,744	-0,275	-0,47	0,067	-0,556	-0,618	-0,796
3 SO2510	5	-0,353	0,011	0,546	-0,634	-0,636	-0,591	-0,518	-0,433	0,32	-0,536	-0,562	-0,776
3 SO610	5	-0,177	0,251	0,758	-0,634	-0,633	-0,551	-0,553	-0,184	0,387	-0,308	-0,428	-0,622
4 SO0_10	5	-0,604	-0,172	0,561	-0,542	-0,547	-0,156	-0,876	-0,474	0,762	-0,572	-0,467	-0,686
4 SO2510	5	-0,209	0,26	0,825	-0,524	-0,525	-0,25	-0,73	-0,037	0,634	-0,162	-0,253	-0,432
4 SO610	5	0,036	0,456	0,878	-,879*	-0,878	-0,687	-0,429	-0,409	0,362	-0,516	-0,702	-0,798
1SO25I15	10	0,487	,754*	,822*	-,915*	-,911*	-,791*	0,015	-0,394	0,041	-0,457	-,767*	-,697*
1SO6_I15	10	0,48	,785*	,891*	-,929*	-,926*	-,779*	-0,048	-0,354	0,101	-0,427	-,747*	-,690*
2SO25I15	10	0,441	,745*	,864*	-,895*	-,891*	-,789*	-0,056	-0,323	0,079	-0,401	-,712*	-,678*
2SO6_I15	10	0,399	,713*	,868*	-,937*	-,934*	-,788*	-0,093	-0,407	0,124	-0,483	-,775*	-,741*
3SO0_I15	5	0,437	0,634	0,652	-,897*	-,893*	-,948*	0,157	-0,49	-0,17	-0,543	-0,831	-0,786
3SO25I15	5	0,476	0,758	0,84	-,926*	-,922*	-0,864	0,016	-0,37	0,003	-0,442	-0,766	-0,722
3SO6_I15	5	0,453	0,742	0,858	-,964*	-,962*	-0,7	-0,071	-0,489	0,178	-0,546	-0,829	-0,736
4SO0_I15	5	0,11	0,446	0,77	-,988*	-,988*	-0,727	-0,272	-0,691	0,285	-0,76	-,927*	-,937*
4SO25I15	5	0,471	0,779	,896*	-,944*	-,941*	-0,762	-0,066	-0,384	0,13	-0,455	-0,768	-0,705
4SO6_I15	5	0,334	0,644	0,824	-,949*	-,946*	-0,863	-0,088	-0,46	0,075	-0,539	-0,814	-0,81
1SO25_I2	10	0,545	,779*	,785*	-,887*	-,883*	-,803*	0,095	-0,365	-0,033	-0,421	-,746*	-,658*
1 SO6_I2	10	0,464	,750*	,847*	-,920*	-,917*	-,764*	-0,033	-0,392	0,091	-0,458	-,762*	-,698*
2SO25_I2	10	0,469	,742*	,829*	-,922*	-,920*	-,725*	-0,027	-0,43	0,111	-0,488	-,781*	-,698*
2 SO6_I2	10	0,337	,655*	,853*	-,960*	-,959*	-,691*	-0,165	-0,516	0,238	-0,582	-,830*	-,779*
3 SO0_I2	5	0,567	0,67	0,529	-0,807	-0,802	-,961*	0,363	-0,421	-0,36	-0,454	-0,767	-0,678
3SO25_I2	5	0,644	0,83	0,736	-0,859	-0,854	-,895*	0,243	-0,307	-0,199	-0,358	-0,721	-0,621
3SO6_I2	5	0,434	0,698	0,791	-,960*	-,957*	-0,86	0,018	-0,495	0,015	-0,557	-0,849	-0,794
4SO0_I2	5	0,281	0,563	0,748	-,979*	-,978*	-0,839	-0,079	-0,617	0,092	-0,68	-,911*	-,888*
4SO25_I2	5	0,476	0,768	0,872	-,956*	-,954*	-0,741	-0,05	-0,439	0,137	-0,502	-0,804	-0,721
4SO6_I2	5	0,392	0,64	0,733	-,948*	-,945*	-,899*	0,042	-0,526	-0,036	-0,587	-0,863	-0,824

Marked correlations are significant at p < ,05000 ; N = 10, |r| ≧ 0,63 and N = 5, |r| ≧ 0,88

	N	PPSCOMP5	PPSCOM10	PPSCOM52	UNGER	BRIGHTNE	Y_VALUE	OPACITY	L_SCAT	L_	A_	B_	INKD09AV
GRAMMAGE	10	,785*	-,741*	0,08	-0,345	,815*	,857*	0,025	0,567	,878*	-0,116	-0,341	-,728*
THICKNES	10	,900*	-0,495	0,409	0,008	0,603	,682*	-0,013	0,241	,690*	0,231	0,083	-,670*
BULK	10	,666*	0,075	,697*	0,571	0,038	0,134	-0,127	-0,398	0,114	0,6	,657*	-0,3
ASH550°C	10	-,767*	0,017	-,705*	-0,558	-0,286	-0,358	,636*	,634*	-0,334	-0,063	-0,467	0,566
ASH925°C	10	-,761*	0,014	-,702*	-0,564	-0,282	-0,353	,641*	,642*	-0,328	-0,062	-0,467	0,562
EMCO_S	10	-,838*	-0,042	-,824*	0,168	-0,336	-0,418	0,257	0,094	-0,449	0,025	-0,376	0,61
FORMATIO	10	0,393	-,646*	-0,207	-,780*	,742*	,728*	0,035	,739*	,770*	-0,569	-,665*	-0,556
BENDTSEN	10	-0,204	-0,035	-0,217	-0,563	-0,174	-0,164	,940*	,833*	-0,123	0,484	-0,09	0,324
PERMEABI	10	-0,307	0,365	0,038	,913*	-0,512	-0,508	-0,19	-,745*	-0,568	0,455	0,471	0,403
PPS_5	10	-0,237	-0,12	-0,324	-0,606	-0,104	-0,106	,903*	,878*	-0,067	0,373	-0,214	0,299
PPS_10	10	-0,628	0,056	-0,538	-0,511	-0,348	-0,387	,853*	,714*	-0,358	0,274	-0,263	0,58
PPS_20	10	-0,475	-0,258	-,673*	-0,536	-0,047	-0,093	,733*	,821*	-0,07	0,099	-0,502	0,357
PPSCOMP5	10	1	-0,405	0,581	0,025	,660*	,739*	-0,327	0,006	,747*	-0,02	0,13	-,811*
PPSCOM10	10	-0,405	1	0,51	0,101	-,917*	-,888*	0,309	-0,396	-,871*	0,531	,798*	,639*
PPSCOM52	10	0,581	0,51	1	0,114	-0,197	-0,097	-0,027	-0,345	-0,074	0,46	,835*	-0,192
UNGER	10	0,025	0,101	0,114	1	-0,159	-0,147	-0,518	-,840*	-0,215	0,234	0,361	0,038
BRIGHTNE	10	,660*	-,917*	-0,197	-0,159	1	,994*	-0,474	0,285	,989*	-0,615	-,651*	-,838*
Y_VALUE	10	,739*	-,888*	-0,097	-0,147	,994*	1	-0,454	0,274	,997*	-0,542	-0,567	-,867*
OPACITY	10	-0,327	0,309	-0,027	-0,518	-0,474	-0,454	1	,666*	-0,408	,632*	0,184	0,52
L_SCAT	10	0,006	-0,396	-0,345	-,840*	0,285	0,274	,666*	1	0,324	-0,033	-0,493	-0,051
L_	10	,747*	-,871*	-0,074	-0,215	,989*	,997*	-0,408	0,324	1	-0,536	-0,562	-,865*
A_	10	-0,02	0,531	0,46	0,234	-0,615	-0,542	,632*	-0,033	-0,536	1	,762*	0,425
B_	10	0,13	,798*	,835*	0,361	-,651*	-0,567	0,184	-0,493	-0,562	,762*	1	0,278
INKD09AV	10	-,811*	,639*	-0,192	0,038	-,838*	-,867*	0,52	-0,051	-,865*	0,425	0,278	1
INKD10AV	10	-,837*	0,374	-0,452	-0,254	-,633*	-,682*	,661*	0,313	-,668*	0,267	-0,053	,905*
PTD09AV	10	-0,359	0,526	0,127	0,576	-0,439	-0,466	-0,57	-,881*	-0,504	-0,174	0,322	0,284
PTD10AV	10	-0,402	0,596	0,149	0,556	-0,517	-0,541	-0,495	-,865*	-0,576	-0,107	0,375	0,361
STRD09AV	10	-0,51	,836*	0,262	0,423	-,782*	-,790*	-0,146	-,726*	-,807*	0,192	0,581	0,566
STRD10AV	10	-0,58	,850*	0,21	0,402	-,827*	-,839*	-0,08	-,685*	-,856*	0,22	0,565	,646*
PD_I15AV	10	,773*	-0,595	0,195	0,123	,818*	,838*	-,728*	-0,17	,824*	-0,531	-0,259	-,959*
PD_I20AV	10	,774*	-0,419	0,352	0,285	,671*	,704*	-,774*	-0,368	,684*	-0,405	-0,047	-,898*
PT_I15AV	10	-0,15	0,474	0,277	0,626	-0,324	-0,334	-,673*	-,940*	-0,372	-0,172	0,387	0,108
PT_I20AV	10	-0,207	0,521	0,265	0,593	-0,378	-0,39	-0,628	-,922*	-0,425	-0,159	0,395	0,168
STR_I15A	10	-0,347	,805*	0,388	0,509	-,695*	-,690*	-0,278	-,829*	-,712*	0,176	,643*	0,425
STR_I20A	10	-0,376	,800*	0,356	0,49	-,695*	-,695*	-0,282	-,819*	-,716*	0,144	0,613	0,438
1 SO25_9	10	0,452	0,281	,675*	0,46	-0,077	-0,011	-0,326	-0,563	-0,025	0,275	0,606	0,01
1 SO6_9	10	,729*	0,119	,792*	0,411	0,117	0,207	-0,293	-0,438	0,199	0,345	0,613	-0,311
2 SO25_9	10	,681*	0,286	,897*	0,354	-0,051	0,052	-0,112	-0,394	0,054	0,525	,768*	-0,298
2 SO6_9	10	0,504	0,344	,782*	0,554	-0,166	-0,079	-0,201	-0,572	-0,095	0,52	,772*	-0,032
3 SO0_9	5	0,384	0,489	0,794	0,49	-0,183	-0,125	-0,538	-0,808	-0,138	0,105	0,698	-0,123
3 SO25_9	5	0,233	0,731	0,87	0,474	-0,522	-0,442	-0,093	-0,672	-0,446	0,576	,960*	0,126
3 SO6_9	5	0,656	-0,54	0,138	0,663	0,568	0,604	-0,588	-0,383	0,555	-0,013	-0,006	-0,633
4 SO0_9	5	0,342	0,445	0,717	0,749	-0,249	-0,186	-0,478	-0,877	-0,218	0,331	0,761	-0,051
4 SO25_9	5	0,468	0,475	0,866	0,559	-0,293	-0,198	-0,116	-0,595	-0,21	0,639	,898*	-0,123
4 SO6_9	5	0,604	0,326	0,86	0,58	-0,099	-0,007	-0,31	-0,638	-0,023	0,461	0,791	-0,296
1 SO2510	10	0,345	0,327	0,617	0,498	-0,212	-0,142	-0,116	-0,485	-0,158	0,495	,667*	0,149
1 SO610	10	,732*	0,129	,806*	0,406	0,068	0,168	-0,147	-0,358	0,163	0,5	,668*	-0,287
2 SO2510	10	0,604	0,307	,845*	0,299	-0,127	-0,023	0,066	-0,276	-0,017	,646*	,775*	-0,21
2 SO610	10	0,501	0,402	,832*	0,458	-0,241	-0,143	-0,005	-0,443	-0,148	,674*	,844*	-0,005
3 SO0_10	5	0,352	0,652	,909*	0,127	-0,308	-0,237	-0,217	-0,532	-0,219	0,212	0,774	-0,068
3 SO2510	5	0,245	0,75	,897*	0,324	-0,474	-0,401	-0,154	-0,643	-0,395	0,41	,902*	0,088
3 SO610	5	0,341	0,675	,923*	0,367	-0,468	-0,374	0,054	-0,507	-0,368	0,681	,975*	0,026
4 SO0_10	5	-0,043	0,734	0,613	0,707	-0,629	-0,581	-0,208	-0,851	-0,609	0,507	0,862	0,363
4 SO2510	5	0,202	0,593	0,722	0,56	-0,532	-0,446	0,157	-0,498	-0,459	0,851	,934*	0,153
4 SO610	5	0,602	0,387	,911*	0,498	-0,135	-0,039	-0,259	-0,6	-0,048	0,471	0,825	-0,283
1SO25I15	10	,892*	-0,132	,722*	0,334	0,392	0,478	-0,419	-0,342	0,47	0,148	0,412	-,667*
1SO6_I15	10	,894*	-0,095	,757*	0,377	0,342	0,434	-0,369	-0,354	0,426	0,245	0,48	-0,63
2SO25I15	10	,859*	-0,022	,789*	0,33	0,278	0,372	-0,315	-0,337	0,368	0,274	0,521	-,634*
2SO6_I15	10	,854*	-0,017	,788*	0,39	0,281	0,372	-0,393	-0,414	0,364	0,234	0,523	-0,546
3SO0_I15	5	,889*	-0,036	0,803	0,134	0,392	0,473	-0,471	-0,323	0,481	-0,029	0,395	-0,729
3SO25I15	5	,910*	-0,045	0,816	0,28	0,336	0,43	-0,365	-0,33	0,43	0,199	0,494	-0,707
3SO6_I15	5	0,872	-0,205	0,638	0,497	0,43	0,508	-0,538	-0,451	0,486	0,112	0,366	-0,714
4SO0_I15	5	0,695	0,131	0,769	0,551	0,159	0,232	-0,613	-0,695	0,211	0,097	0,561	-0,473
4SO25I15	5	,891*	-0,112	0,738	0,415	0,354	0,444	-0,405	-0,383	0,432	0,228	0,467	-0,696
4SO6_I15	5	0,84	0,085	0,865	0,333	0,225	0,318	-0,406	-0,447	0,316	0,204	0,579	-0,609
1SO25_I2	10	,914*	-0,188	,692*	0,271	0,45	0,534	-0,41	-0,276	0,529	0,103	0,35	-,734*
1 SO6_I2	10	,875*	-0,115	,721*	0,376	0,363	0,45	-0,412	-0,367	0,44	0,184	0,437	-,703*
2SO25_I2	10	,868*	-0,177	,660*	0,414	0,411	0,491	-0,47	-0,386	0,476	0,128	0,375	-,731*
2 SO6_I2	10	,803*	-0,075	,689*	0,525	0,309	0,388	-0,519	-0,521	0,367	0,161	0,459	-0,598
3 SO0_I2	5	,922*	-0,18	0,705	-0,034	0,536	0,609	-0,452	-0,155	0,624	-0,163	0,221	-0,826
3SO25_I2	5	,978*	-0,224	0,72	0,116	0,519	0,606	-0,363	-0,155	0,613	0,054	0,306	-0,845
3SO6_I2	5	,898*	-0,075	0,777	0,323	0,38	0,465	-0,494	-0,408	0,459	0,079	0,438	-0,717
4SO0_I2	5	0,814	0,029	0,791	0,39	0,292	0,37	-0,574	-0,542	0,36	0,039	0,485	-0,619
4SO25_I2	5	,892*	-0,172	0,687	0,445	0,409	0,493	-0,478	-0,409	0,476	0,156	0,404	-0,72
4SO6_I2	5	0,877	-0,021	0,805	0,267	0,354	0,437	-0,503	-0,415	0,436	0,035	0,448	-0,695

Marked correlations are significant at p < ,05000 ; N = 10, |r| ≧ 0,63 and N = 5, |r |≧ 0,88

	N	INKD10AV	PTD09AV	PTD10AV	STRD09AV	STRD10AV	PD_I15AV	PD_I20AV	PT_I15AV	PT_I20AV	STRI15AV	STRI20AV
GRAMMAGE	10	-0,51	-,813*	-,853*	-,920*	-,950*	0,583	0,449	-,686*	-,730*	-,850*	-,867*
THICKNES	10	-0,621	-,642*	-,670*	-,696*	-,737*	0,554	0,524	-0,47	-0,524	-0,579	-0,612
BULK	10	-0,536	-0,053	-0,055	-0,03	-0,073	0,296	0,437	0,111	0,066	0,11	0,067
ASH550°C	10	,829*	-0,278	-0,239	-0,087	-0,008	-,672*	-,807*	-0,477	-0,423	-0,278	-0,248
ASH925°C	10	,827*	-0,287	-0,248	-0,095	-0,016	-,670*	-,806*	-0,485	-0,431	-0,285	-0,255
EMCO_S	10	,713*	0,094	0,112	0,139	0,212	-0,601	-,651*	-0,093	-0,063	-0,01	0,012
FORMATIO	10	-0,23	-,649*	-,686*	-,769*	-,784*	0,44	0,237	-0,612	-0,623	-,772*	-,759*
BENDTSEN	10	0,565	-,783*	-,730*	-0,449	-0,385	-0,558	-,667*	-,874*	-,844*	-0,578	-0,581
PERMEABI	10	0,114	0,583	0,598	0,592	0,603	-0,275	-0,101	0,561	0,555	0,611	0,597
PPS_5	10	0,576	-,797*	-,750*	-0,498	-0,432	-0,529	-,663*	-,898*	-,868*	-,635*	-,633*
PPS_10	10	,824*	-0,486	-0,432	-0,192	-0,109	-,747*	-,861*	-,660*	-0,611	-0,374	-0,359
PPS_20	10	,677*	-,641*	-0,611	-0,452	-0,376	-0,534	-,700*	-,793*	-,760*	-0,618	-0,602
PSCOMP5	10	-,837*	-0,359	-0,402	-0,51	-0,58	,773*	,774*	-0,15	-0,207	-0,347	-0,376
PPSCOM10	10	0,374	0,526	0,596	,836*	,850*	-0,595	-0,419	0,474	0,521	,805*	,800*
PPSCOM52	10	-0,452	0,127	0,149	0,262	0,21	0,195	0,352	0,277	0,265	0,388	0,356
UNGER	10	-0,254	0,576	0,556	0,423	0,402	0,123	0,285	0,626	0,593	0,509	0,49
BRIGHTNE	10	-,633*	-0,439	-0,517	-,782*	-,827*	,818*	,671*	-0,324	-0,378	-,695*	-,695*
Y_VALUE	10	-,682*	-0,466	-0,541	-,790*	-,839*	,838*	,704*	-0,334	-0,39	-,690*	-,695*
OPACITY	10	,661*	-0,57	-0,495	-0,146	-0,08	-,728*	-,774*	-,673*	-0,628	-0,278	-0,282
L_SCAT	10	0,313	-,881*	-,865*	-,726*	-,685*	-0,17	-0,368	-,940*	-,922*	-,829*	-,819*
L_	10	-,668*	-0,504	-0,576	-,807*	-,856*	,824*	,684*	-0,372	-0,425	-,712*	-,716*
A_	10	0,267	-0,174	-0,107	0,192	0,22	-0,531	-0,405	-0,172	-0,159	0,176	0,144
B_	10	-0,053	0,322	0,375	0,581	0,565	-0,259	-0,047	0,387	0,395	,643*	0,613
INKD09AV	10	,905*	0,284	0,361	0,566	,646*	-,959*	-,898*	0,108	0,168	0,425	0,438
INKD10AV	10	1	-0,016	0,06	0,266	0,358	-,941*	-,982*	-0,219	-0,158	0,079	0,099
PTD09AV	10	-0,016	1	,992*	,884*	,858*	-0,052	0,109	,973*	,984*	,915*	,926*
PTD10AV	10	0,06	,992*	1	,917*	,902*	-0,136	0,03	,960*	,975*	,940*	,949*
STRD09AV	10	0,266	,884*	,917*	1	,991*	-0,416	-0,232	,817*	,850*	,977*	,980*
STRD10AV	10	0,358	,858*	,902*	,991*	1	-0,497	-0,321	,778*	,816*	,958*	,963*
PD_I15AV	10	-,941*	-0,052	-0,136	-0,416	-0,497	1	,970*	0,128	0,066	-0,253	-0,261
PD_I20AV	10	-,982*	0,109	0,03	-0,232	-0,321	,970*	1	0,303	0,241	-0,048	-0,062
PT_I15AV	10	-0,219	,973*	,960*	,817*	,778*	0,128	0,303	1	,997*	,894*	,897*
PT_I20AV	10	-0,158	,984*	,975*	,850*	,816*	0,066	0,241	,997*	1	,915*	,921*
STR_I15A	10	0,079	,915*	,940*	,977*	,958*	-0,253	-0,048	,894*	,915*	1	,999*
STR_I20A	10	0,099	,926*	,949*	,980*	,963*	-0,261	-0,062	,897*	,921*	,999*	1
1 SO25_9	10	-0,277	0,329	0,35	0,291	0,262	0,134	0,277	0,445	0,424	0,401	0,38
1 SO6_9	10	-0,537	0,093	0,087	0,065	0,006	0,36	0,482	0,252	0,217	0,204	0,17
2 SO25_9	10	-0,559	0,037	0,05	0,124	0,07	0,29	0,447	0,213	0,177	0,266	0,222
2 SO6_9	10	-0,35	0,235	0,26	0,258	0,24	0,124	0,295	0,375	0,349	0,396	0,363
3 SO0_9	5	-0,491	0,631	0,593	0,511	0,469	0,28	0,463	0,786	0,761	0,721	0,702
3 SO25_9	5	-0,241	0,491	0,477	0,632	0,575	-0,074	0,132	0,575	0,571	0,759	0,726
3 SO6_9	5	-0,738	-0,057	-0,161	-0,427	-0,442	0,708	0,752	0,111	0,048	-0,219	-0,232
4 SO0_9	5	-0,44	0,606	0,552	0,497	0,454	0,196	0,395	0,733	0,707	0,696	0,673
4 SO25_9	5	-0,455	0,264	0,223	0,352	0,287	0,137	0,328	0,392	0,37	0,515	0,474
4 SO6_9	5	-0,625	0,271	0,214	0,24	0,179	0,344	0,526	0,444	0,407	0,45	0,413
1 SO2510	10	-0,139	0,22	0,261	0,276	0,263	-0,045	0,11	0,318	0,3	0,357	0,331
1 SO610	10	-0,504	-0,029	-0,022	0,009	-0,045	0,295	0,422	0,135	0,097	0,137	0,097
2 SO2510	10	-0,42	-0,077	-0,042	0,087	0,049	0,155	0,297	0,08	0,049	0,198	0,15
2 SO610	10	-0,297	0,099	0,139	0,216	0,197	0,041	0,213	0,237	0,215	0,333	0,296
3 SO0_10	5	-0,375	0,446	0,445	0,525	0,47	0,133	0,299	0,582	0,572	0,676	0,65
3 SO2510	5	-0,267	0,526	0,521	0,646	0,591	-0,019	0,175	0,627	0,623	0,78	0,752
3 SO610	5	-0,297	0,282	0,27	0,493	0,425	-0,039	0,153	0,379	0,373	0,61	0,569
4 SO0_10	5	-0,03	0,726	0,708	0,785	0,75	-0,234	-0,027	0,747	0,753	,885*	0,866
4 SO2510	5	-0,148	0,231	0,21	0,456	0,398	-0,183	0,001	0,271	0,27	0,533	0,492
4 SO610	5	-0,609	0,259	0,21	0,269	0,204	0,317	0,5	0,432	0,399	0,471	0,432
1SO25I15	10	-,837*	-0,048	-0,074	-0,174	-0,25	,690*	,784*	0,17	0,113	0,004	-0,029
1SO6_I15	10	-,808*	-0,058	-0,088	-0,154	-0,228	,636*	,736*	0,15	0,095	0,023	-0,015
2SO25I15	10	-,819*	-0,058	-0,08	-0,11	-0,185	0,618	,728*	0,154	0,1	0,065	0,024
2SO6_I15	10	-,753*	0,021	0,005	-0,088	-0,147	0,592	,702*	0,23	0,18	0,097	0,064
3SO0_I15	5	-,912*	0	-0,057	-0,163	-0,219	0,759	0,856	0,257	0,201	0,085	0,056
3SO25I15	5	-,903*	-0,08	-0,146	-0,194	-0,256	0,703	0,815	0,166	0,109	0,047	0,01
3SO6_I15	5	-,916*	0,001	-0,087	-0,243	-0,291	0,762	0,868	0,239	0,175	0,015	-0,014
4SO0_I15	5	-0,784	0,347	0,276	0,131	0,083	0,591	0,747	0,566	0,515	0,392	0,366
4SO25I15	5	-,898*	-0,065	-0,143	-0,219	-0,277	0,704	0,818	0,172	0,112	0,026	-0,01
4SO6_I15	5	-0,854	0,069	0,007	-0,041	-0,103	0,636	0,771	0,307	0,254	0,204	0,168
1SO25_I2	10	-,877*	-0,103	-0,138	-0,232	-0,315	,736*	,814*	0,115	0,056	-0,057	-0,09
1 SO6_I2	10	-,865*	-0,036	-0,07	-0,159	-0,233	,705*	,800*	0,178	0,121	0,027	-0,009
2SO25_I2	10	-,893*	-0,021	-0,058	-0,165	-0,243	,739*	,832*	0,196	0,133	0,019	-0,018
2 SO6_I2	10	-,825*	0,122	0,094	-0,031	-0,105	,662*	,786*	0,331	0,272	0,152	0,118
3 SO0_I2	5	-,932*	-0,139	-0,191	-0,321	-0,371	0,834	,891*	0,124	0,065	-0,085	-0,11
3SO25_I2	5	-,960*	-0,241	-0,306	-0,388	-0,445	0,817	,886*	0,018	-0,044	-0,153	-0,186
3SO6_I2	5	-,927*	0,014	-0,058	-0,172	-0,228	0,754	0,866	0,267	0,207	0,086	0,055
4SO0_I2	5	-0,876	0,185	0,116	-0,023	-0,076	0,7	0,831	0,429	0,373	0,241	0,213
4SO25_I2	5	-,918*	-0,041	-0,124	-0,245	-0,298	0,748	0,855	0,2	0,137	0,008	-0,024
4SO6_I2	5	-,911*	0,057	-0,008	-0,122	-0,177	0,74	0,854	0,31	0,253	0,136	0,106

5.2.6 Paper properties vs. set-off, Test series 1

Variable specifications of the correlation tables in Appendix 6(7-8).

Short name	Specification
PPS S5	PPS S5, roughness, µm
PPS S10	PPS S10, roughness, µm
PPS S20	PPS S20, roughness, µm
P	PPS S clamping pressure at roughness 4.0 µm (Bristow)
Rppscomp	Relative compressibility of paper as a ratio of PPS 5 and PPS 10
Appscomp	Absolute compressibility of paper as a ratio of PPS 5 and PPS 10
Rppscom1	Relative compressibility of paper as a ratio of PPS 10 and PPS 20
Appscom1	Absolute compressibility of paper as a ratio of PPS 10 and PPS 20
Rppscom5	Relative compressibility of paper as a ratio of PPS 5 and PPS 20
Appscom5	Absolute compressibility of paper as a ratio of PPS 5 and PPS 20
so2I15 1	Set-off 2,5 s at a given ink weight 1.5 g/m², printing conditions 1
so2I15 2	Set-off 2,5 s at a given ink weight 1.5 g/m², printing conditions 2
Rdelta12	Relative delta set-off 2,5 s at a given ink weight 1.5 g/m², printing conditions 1/2
Adelta12	Absolute delta set-off 2,5 s at a given ink weight 1.5 g/m², printing conditions 1-2
so6I15 1	Set-off 60 s at a given ink weight 1.5 g/m², printing conditions 1
so6I15 2	Set-off 60 s at a given ink weight 1.5 g/m², printing conditions 2
Rdelta 1	Relative delta set-off 60 s at a given ink weight 1.5 g/m², printing conditions 1/2
Adelta 1	Absolute delta set-off 60 s at a given ink weight 1.5 g/m², printing conditions 1-2
so2I20 1	Set-off 2,5 s at a given ink weight 2 g/m², printing conditions 1
so2I20 2	Set-off 2,5 s at a given ink weight 2 g/m², printing conditions 2
Rdelta12	Relative delta set-off 2,5 s at a given ink weight 2 g/m², printing conditions 1/2
Adelta12	Absolute delta set-off 2,5 s at a given ink weight 2 g/m², printing conditions 1-2
so6I20 1	Set-off 60 s at a given ink weight 2 g/m², printing conditions 1
so6I20 2	Set-off 60 s at a given ink weight 2 g/m², printing conditions 2
Rdelta12	Relative delta set-off 60 s at a given ink weight 2 g/m², printing conditions 1/2
Adelta12	Absolute delta set-off 60 s at a given ink weight 2 g/m², printing conditions 1-2

5.2.6 Paper properties vs. set-off, Test series 1.

Results of the paper properties for the correlation analysis of roughness and compressibility vs. set-off.

Paper	PPS_S5	PPS_S10	PPS_S20	Clamp P	RPPSCOMP	APPSCOMP	RPPSCOM1	APPSCOM1	RPPSCOM5	APPSCOM5	SO2I15_1	SO2I15_2	RDELTA12
MFS 1 A	5,67	4,27	3,44	11,4	1,33	1,40	1,24	0,83	1,65	2,23	0,43	0,35	1,22
DIP A	5,74	5,10	4,00	20,0	1,13	0,64	1,28	1,10	1,44	1,74	0,28	0,17	1,60
News (dip) A	4,49	3,63	2,65	7,7	1,24	0,86	1,37	0,98	1,69	1,84	0,39	0,31	1,24
MFS 2 A	4,52	3,49	2,99	7,2	1,30	1,03	1,17	0,50	1,51	1,53	0,41	0,29	1,44
News virgin B	4,65	3,79	2,95	8,7	1,23	0,86	1,28	0,84	1,58	1,70	0,37	0,29	1,27
MFS 1 B	5,17	4,15	3,12	11,0	1,25	1,02	1,33	1,03	1,66	2,05	0,42	0,30	1,38
DIP B	5,05	4,35	3,44	13,0	1,16	0,70	1,26	0,91	1,47	1,61	0,27	0,18	1,46
News (dip) B	4,62	3,61	2,81	7,9	1,28	1,01	1,28	0,80	1,64	1,81	0,40	0,28	1,41
MFS 2 B	4,81	3,99	2,93	10,0	1,21	0,82	1,36	1,06	1,64	1,88	0,38	0,28	1,37
News virgin B	4,43	3,67	2,83	7,9	1,21	0,76	1,30	0,84	1,57	1,60	0,42	0,31	1,38

Paper	ADELTA12	SO6I15_1	SO6I15_2	RDELTA_1	ADELTA_1	SO2I20_1	SO2I20_2	RDELTA12	ADELTA12	SO6I20_1	SO6I20_2	RDELTA12	ADELTA12
MFS 1 A	0,08	0,31	0,19	1,59	0,11	0,58	0,46	1,25	0,12	0,44	0,30	1,47	0,14
DIP A	0,10	0,14	0,11	1,30	0,03	0,35	0,25	1,42	0,10	0,20	0,15	1,32	0,05
News (dip) A	0,07	0,26	0,18	1,40	0,07	0,50	0,41	1,24	0,10	0,37	0,28	1,32	0,09
MFS 2 A	0,13	0,26	0,19	1,36	0,07	0,54	0,42	1,28	0,12	0,39	0,30	1,32	0,09
News virgin B	0,08	0,28	0,20	1,43	0,08	0,47	0,41	1,16	0,07	0,40	0,28	1,42	0,12
MFS 1 B	0,11	0,29	0,21	1,38	0,08	0,54	0,40	1,35	0,14	0,38	0,29	1,32	0,09
DIP B	0,08	0,13	0,09	1,34	0,03	0,36	0,26	1,41	0,10	0,20	0,15	1,33	0,05
News (dip) B	0,12	0,26	0,19	1,36	0,07	0,51	0,37	1,38	0,14	0,36	0,28	1,29	0,08
MFS 2 B	0,10	0,26	0,17	1,53	0,09	0,52	0,40	1,29	0,12	0,35	0,27	1,30	0,08
News virgin B	0,12	0,27	0,18	1,44	0,08	0,55	0,42	1,29	0,12	0,36	0,33	1,11	0,04

5.2.6 Paper properties vs. set-off, Test series 1. Roughness and compressibility vs. set-off, correlations

Correlations (siirto compress xx.sta). Marked correlations are significant at p < ,05000

Variable	PPS_S5	PPS_S10	PPS_S20	P	RPPSCOMP	APPSCOMP	RPPSCOM1	APPSCOM1	RPPSCOM5	APPSCOM5	SO2I15_1	SO2I15_2	RDELTA12
PPS_S5	1,0000	,8980*	,8953*	,8440*	-,1766	,1979	-,1396	,4389	-,2692	,5531	-,3724	-,3048	,2572
PPS_S10	,8980*	1,0000	,9413*	,9863*	-,5891	-,2536	,0033	,6184	-,5092	,2399	-,6765*	-,6330*	,5178
PPS_S20	,8953*	,9413*	1,0000	,9422*	-,4436	-,1288	-,3340	,3167	-,6665*	,1240	-,6449*	-,6317	,5741
P	,8440*	,9863*	,9422*	1,0000	-,6424*	-,3418	-,0386	,5777	-,5912	,1179	-,7305*	-,7143*	,6220
RPPSCOMP	-,1766	-,5891	-,4436	-,6424*	1,0000	,9241*	-,3202	-,6224	,6025	,4362	,8145*	,8236*	-,6278
APPSCOMP	,1979	-,2536	-,1288	-,3418	,9241*	1,0000	-,3142	-,4128	,5424	,6815*	,6882*	,7400*	-,5880
RPPSCOM1	-,1396	,0033	-,3340	-,0386	-,3202	-,3142	1,0000	,7866*	,5629	,3136	,0190	,1139	-,2793
APPSCOM1	,4389	,6184	,3167	,5777	-,6224	-,4128	,7866*	1,0000	,1208	,3852	-,3993	-,3080	,1185
RPPSCOM5	-,2692	-,5092	-,6665*	-,5912	,6025	,5424	,5629	,1208	1,0000	,6466*	,7231*	,8122*	-,7833*
APPSCOM5	,5531	,2399	,1240	,1179	,4362	,6815*	,3136	,3852	,6466*	1,0000	,3765	,5023	-,5006
SO2I15_1	-,3724	-,6765*	-,6449*	-,7305*	,8145*	,6882*	,0190	-,3993	,7231*	,3765	1,0000	,9458*	-,6311
SO2I15_2	-,3048	-,6330*	-,6317	-,7143*	,8236*	,7400*	,1139	-,3080	,8122*	,5023	,9458*	1,0000	-,8419*
RDELTA12	,2572	,5178	,5741	,6220	-,6278	-,5880	-,2793	,1185	-,7833*	-,5006	-,6311	-,8419*	1,0000
ADELTA12	-,2427	-,2058	-,1127	-,1312	,0658	-,0749	-,2790	-,3160	-,1816	-,3298	,2745	-,0526	,5524
SO6I15_1	-,3069	-,6218	-,6249	-,6954*	,8009*	,7106*	,1122	-,2925	,7911*	,4849	,9513*	,9669*	-,7652*
SO6I15_2	-,4045	-,6881*	-,6819*	-,7351*	,7848*	,6435*	,0911	-,3458	,7607*	,3742	,9424*	,9175*	-,6755*
RDELTA_1	,0875	-,1727	-,2138	-,2990	,4804	,5770	,1657	,0126	,5521	,5947	,5547	,6901*	-,7163*
ADELTA_1	-,1177	-,4463	-,4636	-,5532	,7350*	,7357*	,1328	-,1749	,7490*	,6048	,8570*	,9349*	-,8199*
SO2I20_1	-,3211	-,6465*	-,6114	-,7127*	,8364*	,7343*	,0075	-,3930	,7315*	,4283	,9899*	,9531*	-,6599*
SO2I20_2	-,3690	-,6754*	-,6403*	-,7437*	,8075*	,6933*	,0179	-,4070	,7144*	,3755	,9500*	,9759*	-,7852*
RDELTA12	,4102	,5520	,5402	,5980	-,4518	-,3277	-,0746	,2932	-,4520	-,0965	-,5394	-,6939*	,8051*
ADELTA12	,0667	-,0841	-,0746	-,0953	,3230	,3341	-,0318	-,0628	,2559	,2880	,4007	,1880	,2237
SO6I20_1	-,3227	-,6594*	-,6101	-,7238*	,8654*	,7595*	-,0302	-,4322	,7268*	,4222	,9388*	,9666*	-,7799*
SO6I20_2	-,5072	-,7552*	-,7287*	-,7972*	,7409*	,5674	,0471	-,4255	,6825*	,2330	,9757*	,9328*	-,6562*
RDELTA12	,4908	,2447	,3114	,1795	,3511	,5338	-,2218	-,0374	,1216	,5108	-,0831	,1167	-,3682
ADELTA12	,1491	-,2224	-,1498	-,3039	,7614*	,8234*	-,1634	-,2763	,5263	,6123	,5036	,6532*	-,7077*

Variable	ADELTA12	SO6I15_1	SO6I15_2	RDELTA_1	ADELTA_1	SO2I20_1	SO2I20_2	RDELTA12	ADELTA12	SO6I20_1	SO6I20_2	RDELTA12	ADELTA12
PPS_S5	-,2427	-,3069	-,4045	,0875	-,1177	-,3211	-,3690	,4102	,0667	-,3227	-,5072	,4908	,1491
PPS_S10	-,2058	-,6218	-,6881*	-,1727	-,4463	-,6465*	-,6754*	,5520	-,0841	-,6594*	-,7552*	,2447	-,2224
PPS_S20	-,1127	-,6249	-,6819*	-,2138	-,4636	-,6114	-,6403*	,5402	-,0746	-,6101	-,7287*	,3114	-,1498
P	-,1312	-,6954*	-,7351*	-,2990	-,5532	-,7127*	-,7437*	,5980	-,0953	-,7238*	-,7972*	,1795	-,3039
RPPSCOMP	,0658	,8009*	,7848*	,4804	,7350*	,8364*	,8075*	-,4518	,3230	,8654*	,7409*	,3511	,7614*
APPSCOMP	-,0749	,7106*	,6435*	,5770	,7357*	,7343*	,6933*	-,3277	,3341	,7595*	,5674	,5338	,8234*
RPPSCOM1	-,2790	,1122	,0911	,1657	,1328	,0075	,0179	-,0746	-,0318	-,0302	,0471	-,2218	-,1634
APPSCOM1	-,3160	-,2925	-,3458	,0126	-,1749	-,3930	-,4070	,2932	-,0628	-,4322	-,4255	-,0374	-,2763
RPPSCOM5	-,1816	,7911*	,7607*	,5521	,7490*	,7315*	,7144*	-,4520	,2559	,7268*	,6825*	,1216	,5263
APPSCOM5	-,3298	,4849	,3742	,5947	,6048	,4283	,3755	-,0965	,2880	,4222	,2330	,5108	,6123
SO2I15_1	,2745	,9513*	,9424*	,5547	,8570*	,9899*	,9500*	-,5394	,4007	,9388*	,9757*	-,0831	,5036
SO2I15_2	-,0526	,9669*	,9175*	,6901*	,9349*	,9531*	,9759*	-,6939*	,1880	,9666*	,9328*	,1167	,6532*
RDELTA12	,5524	-,7652*	-,6755*	-,7163*	-,8199*	-,6599*	-,7852*	,8051*	,2237	-,7799*	-,6562*	-,3682	-,7077*
ADELTA12	1,0000	,0620	,1811	-,3377	-,1333	,2219	,0317	,3964	,6756*	,0247	,2384	-,6012	-,3856
SO6I15_1	,0620	1,0000	,9725*	,6365*	,9296*	,9401*	,9594*	-,6844*	,1955	,9816*	,9394*	,1363	,6777*
SO6I15_2	,1811	,9725*	1,0000	,4408	,8182*	,9039*	,9072*	-,6240	,2372	,9503*	,9343*	,0608	,6096
RDELTA_1	-,3377	,6365*	,4408	1,0000	,8735*	,6413*	,7020*	-,5760	-,0201	,6356*	,5414	,2815	,5645
ADELTA_1	-,1333	,9296*	,8182*	,8735*	1,0000	,8903*	,9327*	-,7019*	,1072	,9192*	,8405*	,2402	,7082*
SO2I20_1	,2219	,9401*	,9039*	,6413*	,8903*	1,0000	,9592*	-,5374	,4063	,9355*	,9543*	-,0345	,5354
SO2I20_2	,0317	,9594*	,9072*	,7020*	,9327*	,9592*	1,0000	-,7529*	,1314	,9762*	,9554*	,0822	,6345*
RDELTA12	,3964	-,6844*	-,6240	-,5760	-,7019*	-,5374	-,7529*	1,0000	,5489	-,7385*	-,6439*	-,2936	-,6277
ADELTA12	,6756*	,1955	,2372	-,0201	,1072	,4063	,1314	,5489	1,0000	,1251	,2583	-,3866	-,1734
SO6I20_1	,0247	,9816*	,9503*	,6356*	,9192*	,9355*	,9762*	-,7385*	,1251	1,0000	,9326*	,2072	,7363*
SO6I20_2	,2384	,9394*	,9343*	,5414	,8405*	,9543*	,9554*	-,6439*	,2583	,9326*	1,0000	-,1593	,4425
RDELTA12	-,6012	,1363	,0608	,2815	,2402	-,0345	,0822	-,2936	-,3866	,2072	-,1593	1,0000	,8134*
ADELTA12	-,3856	,6777*	,6096	,5645	,7082*	,5354	,6345*	-,6277	-,1734	,7363*	,4425	,8134*	1,0000

5.3 Sheet mould papers made of different furnishes vs. set-off - Test series 2

Prüfbau printing results

	Calendering 1+1				*Calendering 3+3*			
Point	**Ink transf. 2.5 s g/m^2**	**Set-off 2.5 s D**	**Ink transf. 60 s g/m^2**	**Set-off 60 s D**	**Ink transf. 2.5 s g/m^2**	**Set-off 2.5 s D**	**Ink transf. 60 s g/m^2**	**Set-off 60 s D**
100% TMP	1,97	0,198	1,446	0,191	1,24	0,258	1,178	0,165
	3,14	0,345	2,458	0,311	2,30	0,509	2,317	0,345
	4,76	0,555	3,558	0,548	3,37	0,702	3,456	0,523
100% DIP1	2,01	0,169	1,344	0,117	1,27	0,216	1,280	0,127
	3,43	0,362	2,432	0,243	2,19	0,420	2,317	0,305
	5,08	0,545	3,558	0,445	3,24	0,707	3,302	0,530
100% DIP2	1,89	0,154	1,254	0,082	1,27	0,189	1,254	0,101
	3,40	0,320	2,509	0,192	2,38	0,357	2,368	0,227
	5,11	0,533	3,674	0,296	3,29	0,606	3,290	0,359
12,5% ch.pulp	2,00	0,224	1,254	0,137	1,23	0,260	1,280	0,143
	3,46	0,315	2,470	0,261	2,29	0,421	2,394	0,307
	5,02	0,566	3,686	0,495	3,43	0,710	3,456	0,525
25% ch. pulp	1,87	0,166	1,216	0,123	1,15	0,216	1,114	0,149
	3,35	0,394	2,381	0,322	2,38	0,381	2,304	0,278
	4,93	0,493	3,597	0,436	3,48	0,613	3,443	0,515
50% ch. pulp	1,93	0,134	1,267	0,100	1,27	0,202	1,344	0,129
	3,39	0,335	2,394	0,224	2,34	0,361	2,419	0,262
	4,99	0,441	3,712	0,342	3,57	0,567	3,558	0,386
50% DIP1	2,00	0,169	1,344	0,140	1,15	0,210	1,229	0,135
	3,43	0,353	2,432	0,261	2,29	0,470	2,330	0,313
	5,03	0,644	3,430	0,393	3,34	0,708	3,366	0,528
75% DIP1	1,95	0,170	1,357	0,102	1,25	0,227	1,267	0,127
	3,43	0,369	2,458	0,258	2,15	0,453	2,355	0,295
	5,00	0,573	3,597	0,405	3,42	0,687	3,405	0,482
50% DIP2	2,06	0,231	1,280	0,112	1,27	0,238	1,280	0,179
	3,51	0,393	2,394	0,257	2,25	0,512	2,317	0,348
	5,02	0,610	3,546	0,498	3,24	0,730	3,290	0,539
75% DIP2	1,91	0,160	1,280	0,082	1,27	0,246	1,382	0,119
	3,32	0,336	2,496	0,192	2,24	0,479	2,330	0,268
	5,00	0,540	3,661	0,378	3,25	0,765	3,366	0,512
5% filler 1*	1,98	0,195	1,331	0,145	1,23	0,260	1,101	0,141
	3,48	0,500	2,432	0,276	2,32	0,471	2,253	0,351
	5,08	0,693	3,674	0,610	3,33	0,738	3,290	0,548
12% filler 1*	2,05	0,217	1,318	0,115	1,25	0,290	1,242	0,139
	3,44	0,472	2,483	0,274	2,34	0,482	2,291	0,290
	5,00	0,733	3,635	0,511	3,33	0,801	3,226	0,594
20% filler 1*	1,87	0,182	1,267	0,120	1,25	0,335	1,152	0,119
	3,48	0,410	2,419	0,276	2,30	0,525	2,266	0,298
	5,09	0,703	3,507	0,433	3,23	0,753	3,213	0,465
5% filler 2*	1,95	0,209	1,280	0,126	1,19	0,244	1,280	0,171
	3,37	0,347	2,458	0,302	2,27	0,485	2,304	0,366
	4,79	0,595	3,584	0,506	3,26	0,778	3,213	0,569
12% filler 2*	1,91	0,220	1,344	0,123	1,10	0,210	1,203	0,137
	3,40	0,433	2,406	0,255	2,12	0,554	2,112	0,308
	5,02	0,689	3,456	0,494	3,07	0,763	3,187	0,540
20% filler 2*	2,04	0,263	1,254	0,118	1,25	0,281	1,344	0,133
	3,46	0,480	2,381	0,225	2,15	0,535	2,240	0,274
	5,08	0,693	3,366	0,382	3,01	0,774	3,034	0,502
100% CTMP	2,04	0,188	1,229	0,098	1,24	0,219	1,203	0,126
	3,52	0,356	2,470	0,269	2,30	0,364	2,394	0,298
	5,06	0,476	3,763	0,394	3,46	0,617	3,392	0,461
50/50CTMP/DIP	2,02	0,168	1,293	0,112	1,37	0,206	1,318	0,151
	3,39	0,398	2,445	0,250	2,30	0,375	2,317	0,325
	5,06	0,583	3,597	0,465	3,33	0,716	3,443	0,443

*) The numbers are nominal filler % mixed with TMP. Ch. pulp is Chemical pulp.

Calendering 5+5

Point	**Ink transf. 2.5 s g/m^2**	**Set-off 2.5 s D**	**Ink transf. 60 s g/m^2**	**Set-off 60 s D**
100% TMP	1,27	0,319	1,126	0,171
	2,30	0,485	2,266	0,365
	3,32	0,739	3,264	0,572
100% DIP1	1,16	0,249	1,306	0,138
	2,23	0,455	2,202	0,295
	3,14	0,744	3,123	0,526
100% DIP2	1,14	0,206	1,280	0,134
	2,27	0,411	2,214	0,281
	3,19	0,677	3,149	0,496
12,5% ch.pulp	1,22	0,275	1,280	0,183
	2,24	0,474	2,214	0,335
	3,23	0,731	3,251	0,571
25% ch. pulp	1,31	0,229	1,203	0,166
	2,33	0,437	2,266	0,303
	3,34	0,667	3,315	0,540
50% ch. pulp	1,29	0,216	1,216	0,140
	2,29	0,378	2,342	0,277
	3,37	0,604	3,354	0,463
50% DIP1	1,25	0,229	1,254	0,158
	2,24	0,438	2,304	0,346
	3,24	0,790	3,315	0,581
75% DIP1	1,19	0,233	1,344	0,155
	2,18	0,472	2,317	0,354
	3,16	0,696	3,354	0,576
50% DIP2	1,32	0,300	1,229	0,153
	2,30	0,526	2,317	0,310
	3,20	0,787	3,149	0,568
75% DIP2	1,18	0,221	1,357	0,134
	2,19	0,419	2,253	0,312
	3,19	0,705	3,187	0,539
5% filler 1*	1,27	0,290	1,293	0,152
	2,30	0,594	2,240	0,344
	3,15	0,820	3,238	0,576
12% filler 1'	1,15	0,315	1,318	0,143
	2,23	0,533	2,138	0,324
	3,08	0,810	3,072	0,538
20% fliier 1*	1,19	0,280	1,254	0,130
	2,20	0,560	2,202	0,329
	3,10	0,788	3,123	0,550
5% filler 2*	1,25	0,281	1,344	0,170
	2,23	0,550	2,150	0,333
	3,23	0,801	3,162	0,582
12% filler 2*	1,16	0,293	1,267	0,171
	2,05	0,559	2,125	0,407
	3,01	0,834	3,046	0,665
20% filler 2*	1,25	0,311	1,306	0,150
	2,12	0,559	2,048	0,325
	3,05	0,802	2,995	0,549
100% CTMP	1,29	0,234	1,152	0,151
	2,34	0,377	2,381	0,282
	3,38	0,642	3,315	0,522
50/50CTMP/DIP1	1,25	0,219	1,318	0,136
	2,27	0,419	2,291	0,313
	3,20	0,737	3,238	0,540

*) The numbers are nominal filler % mixed with TMP. Ch. pulp is Chemical pulp.

5.3 Test series 2, paper properties and interpolated set-off values at ink transferred 2 g/m^2

Point	Calend. nip times	Furnish	Grammage	Bulk	Filler*)	Light scatt. coef.	Opacity	Bendtsen air permeability	Bendtsen 98 kPa roughness	PPS S5
			g/m^2	cm^3/g	%	m^2/kg	%	ml/min.	ml/min.	µm
TMP1	2	1	41,5	1,93	0,3	47,6	87,7	206	359	6,56
DIP1	2	2	41,1	1,56	6,9	53,3	92,2	145	197	5,47
DIP2	2	3	43,0	1,44	9,6	55,6	93,4	198	158	5,09
12,5 ch.pulp	2	4	41,1	1,85	0,3	45,5	84,8	232	325	6,33
25 ch. pulp	2	5	41,1	1,78	0,3	43,5	82,9	299	295	6,26
50 ch. pulp	2	6	40,8	1,62	0,3	39,7	78,7	459	221	6,10
50 DIP1	2	7	42,0	1,72	3,7	51,8	90,8	149	272	6,15
75 DIP1	2	8	41,4	1,64	5,5	52,5	91,1	142	220	5,77
50 DIP2	2	9	41,2	1,70	5,0	54,6	91,2	197	237	5,78
75 DIP2	2	10	41,4	1,59	7,1	55,1	92,0	225	197	5,55
5 filler1	2	11	42,9	1,87	5,8	58,3	89,7	239	299	6,01
12 filler1	2	12	42,1	1,73	15,5	65,5	89,9	326	219	5,55
20 filler 1	2	13	41,6	1,63	24,5	69,6	90,0	457	189	4,92
5 filler 2	2	14	39,5	1,82	15,8	53,1	88,0	209	292	6,24
12 filler 2	2	15	40,6	1,72	5,5	60,3	90,4	199	240	5,60
20 filler 2	2	16	40,5	1,58	14,6	64,2	90,6	231	195	5,24
CTMP	2	17	41,5	1,76	0,8	43,3	77,9	227	242	6,53
50/50 CTMP/DIP1	2	18	41,7	1,63	3,8	47,6	86,9	158	223	5,97
TMP1	6	1	41,5	1,71	0,3	46,8	87,4	160	199	5,04
DIP1	6	2	41,2	1,38	6,9	51,3	91,8	94	91	4,15
DIP2	6	3	43,1	1,30	9,6	53,0	93,0	161	68	3,92
12,5 ch.pulp	6	4	41,3	1,63	0,3	44,7	84,6	181	180	5,06
25 ch. pulp	6	5	41,0	1,59	0,3	42,9	82,7	219	164	4,82
50 ch. pulp	6	6	40,9	1,46	0,3	38,2	78,0	365	128	4,74
50 DIP1	6	7	42,4	1,52	3,7	51,1	90,9	84	143	4,61
75 DIP1	6	8	41,7	1,46	5,5	51,0	90,8	84	111	4,51
50 DIP2	6	9	41,1	1,51	5,0	52,8	90,8	133	123	4,27
75 DIP2	6	10	41,6	1,40	7,1	53,0	91,6	152	92	4,14
5 filler1	6	11	42,4	1,64	5,8	55,7	88,7	185	139	4,49
12 filler1	6	12	42,3	1,54	15,5	64,4	89,8	254	131	4,06
20 filler 1	6	13	41,3	1,45	24,5	67,5	89,3	391	99	3,74
5 filler 2	6	14	39,6	1,63	15,8	51,7	87,6	144	154	4,64
12 filler 2	6	15	40,5	1,49	5,5	58,0	89,9	138	109	4,22
20 filler 2	6	16	40,4	1,40	14,6	61,1	90,1	182	79	3,93
CTMP	6	17	41,6	1,52	0,8	41,8	77,5	143	108	4,86
50/50 CTMP/DIP1	6	18	41,6	1,46	3,8	45,9	86,1	100	103	4,70
TMP1	10	1	41,2	1,63	0,3	46,6	87,3	149	143	4,65
DIP1	10	2	41,2	1,31	6,9	50,0	91,6	95	70	3,91
DIP2	10	3	42,9	1,24	9,6	51,8	92,7	155	51	3,54
12,5 ch.pulp	10	4	41,0	1,54	0,3	44,4	84,4	163	116	4,43
25 ch. pulp	10	5	41,2	1,50	0,3	42,6	82,7	200	116	4,51
50 ch. pulp	10	6	41,3	1,40	0,3	38,6	78,6	338	95	4,29
50 DIP1	10	7	42,1	1,47	3,7	49,8	90,4	94	114	4,29
75 DIP1	10	8	41,6	1,42	5,5	50,7	90,8	82	95	4,15
50 DIP2	10	9	41,3	1,48	5,0	52,4	90,8	163	107	4,03
75 DIP2	10	10	41,5	1,37	7,1	53,5	91,9	139	83	3,72
5 filler1	10	11	42,5	1,58	5,8	55,9	88,9	184	121	4,28
12 filler1	10	12	41,8	1,48	15,5	63,9	89,6	228	98	3,80
20 filler 1	10	13	41,7	1,41	24,5	67,7	89,7	362	83	3,44
5 filler 2	10	14	39,6	1,56	15,8	52,2	87,8	133	131	4,37
12 filler 2	10	15	40,5	1,43	5,5	58,3	90,0	125	88	3,81
20 filler 2	10	16	40,5	1,36	14,6	59,8	89,8	154	83	3,49
CTMP	10	17	41,9	1,48	0,8	41,9	77,6	130	109	4,83
50/50 CTMP/DIP1	10	18	41,6	1,42	3,8	46,0	86,4	77	90	4,31

*) Filler contents are presented as ash content made at 925 °C and the carbonate points at 575 °C.

5.3 Test series 2, paper properties and interpolated set-off values at ink transferred 2 g/m^2

Point	Furnish	PPS S10	PPS 5/10 compr.	Delta PPS PPS 5-10	Paper gloss	Unger oil absorption	Bending stifness Edana	Set-off 2.5 s	Set-off 60 s
		µm		µm	%	g/m2		D	D
TMP1	1	4,41	1,49	2,15	10,5	20,3	50	0,33	0,26
DIP1	2	3,86	1,42	1,61	11,1	15,9	46	0,29	0,19
DIP2	3	3,57	1,43	1,52	12,0	16,7	45	0,27	0,15
12,5 ch.pulp	4	4,42	1,43	1,91	10,7	21,0	51	0,28	0,22
25 ch. pulp	5	4,38	1,43	1,88	11,0	22,0	48	0,34	0,23
50 ch. pulp	6	4,40	1,39	1,70	11,4	21,6	48	0,27	0,18
50 DIP1	7	4,21	1,46	1,94	10,6	17,4	49	0,29	0,21
75 DIP1	8	4,06	1,42	1,71	10,9	16,9	47	0,3	0,19
50 DIP2	9	3,81	1,52	1,97	10,6	17,7	47	0,32	0,19
75 DIP2	10	3,73	1,49	1,82	11,3	17,7	44	0,28	0,15
5 filler1	11	3,95	1,52	2,06	10,2	21,3	50	0,41	0,22
12 filler1	12	3,64	1,52	1,91	10,2	22,7	45	0,39	0,21
20 filler 1	13	3,24	1,52	1,68	10,5	24,7	40	0,34	0,22
5 filler 2	14	4,13	1,51	2,11	10,4	17,2	47	0,31	0,22
12 filler 2	15	3,66	1,53	1,94	10,8	16,6	44	0,37	0,2
20 filler 2	16	3,39	1,55	1,85	11,7	16,1	42	0,42	0,18
CTMP	17	4,68	1,40	1,85	10,8	19,4	51	0,3	0,2
50/50 CTMP/DIP1	18	4,22	1,41	1,75	11,2	16,7	50	0,32	0,2
TMP1	1	3,40	1,48	1,64	14,1	16,2	49	0,44	0,3
DIP1	2	2,86	1,45	1,29	16,0	13,1	44	0,38	0,26
DIP2	3	2,79	1,41	1,13	16,1	13,4	42	0,3	0,18
12,5 ch.pulp	4	3,52	1,44	1,54	14,2	16,9	49	0,38	0,25
25 ch. pulp	5	3,40	1,42	1,42	15,2	17,4	46	0,33	0,26
50 ch. pulp	6	3,54	1,34	1,20	15,7	17,6	46	0,31	0,21
50 DIP1	7	3,19	1,45	1,42	14,5	13,3	47	0,4	0,26
75 DIP1	8	3,09	1,46	1,42	15,1	13,9	45	0,41	0,24
50 DIP2	9	2,82	1,51	1,45	15,3	14,0	44	0,44	0,26
75 DIP2	10	2,79	1,48	1,35	15,7	12,4	42	0,41	0,22
5 filler1	11	2,99	1,50	1,50	13,9	15,2	46	0,42	0,3
12 filler1	12	2,61	1,56	1,45	14,3	18,0	44	0,42	0,25
20 filler 1	13	2,48	1,51	1,26	15,1	19,1	37	0,47	0,26
5 filler 2	14	3,10	1,50	1,54	14,2		45	0,42	0,3
12 filler 2	15	2,71	1,56	1,51	14,9	12,4	42	0,51	0,29
20 filler 2	16	2,55	1,54	1,38	17,2	11,8	41	0,49	0,24
CTMP	17	3,60	1,35	1,26	15,7	13,0	49	0,32	0,23
50/50 CTMP/DIP1	18	3,35	1,40	1,35	15,1	12,2	47	0,32	0,26
TMP1	1	3,16	1,47	1,49	15,4	14,4	47	0,42	0,32
DIP1	2	2,62	1,49	1,29	18,4	11,1	41	0,41	0,26
DIP2	3	2,47	1,43	1,07	19,8	11,4	41	0,36	0,24
12,5 ch.pulp	4	3,06	1,45	1,37	16,4	14,9	45	0,42	0,3
25 ch. pulp	5	3,19	1,41	1,32	16,3	15,5	43	0,37	0,28
50 ch. pulp	6	3,18	1,35	1,11	17,8	15,4	43	0,33	0,23
50 DIP1	7	2,85	1,51	1,44	16,4	12,4	45	0,38	0,29
75 DIP1	8	2,79	1,49	1,36	17,0	11,6	43	0,48	0,29
50 DIP2	9	2,67	1,51	1,36	16,0	13,5	43	0,46	0,29
75 DIP2	10	2,55	1,46	1,17	18,1	12,6	38	0,38	0,26
5 filler1	11	2,85	1,50	1,43	15,2	15,6	45	0,5	0,3
12 filler1	12	2,48	1,53	1,32	16,0	17,9	43	0,49	0,29
20 filler 1	13	2,33	1,48	1,11	16,6	18,0	38	0,5	0,29
5 filler 2	14	2,91	1,50	1,46	15,6	12,7	43	0,48	0,3
12 filler 2	15	2,47	1,54	1,34	17,4	11,6	42	0,54	0,37
20 filler 2	16	2,29	1,52	1,20	19,5	11,4	40	0,53	0,31
CTMP	17	3,59	1,35	1,24	16,0	13,2	49	0,33	0,25
50/50 CTMP/DIP1	18	3,02	1,43	1,29	17,0	11,4	47	0,37	0,27

*) Filler contents are presented as ash content made at 925 °C and the carbonate points at 575 °C.

5.3 Test series 2. Correlations of paper properties and set-off values interpolated at ink transferred 2 g/m^2.

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+----------+-----------------------------------------------------------------------------------------------------------------------------+
| STAT.    |Correlations (effuset int 18 1-3x.sta)                                                                                       |
| BASIC    |Marked correlations are significant at p < ,05000                                                                            |
| STATS    |                                                                                                                             |
+----------+------+------+------+------+------+------+------+------+------+------+------+------+------+------+------+------+------+------+
|          |CAL_NI|      |GRAMMA|      |LIGHT_|OPACIT|PERMEA|BROUGH|      |      |COMP5_|DELTAP|      |      |      |SO25S_|SO60S_|
| Variable |  PS  |SAMPLE|  GE  | BULK |  SC  |   Y  |  BI  |  NE  | PPS_5|PPS_10|  10  |  PS  | GLOSS| UNGER| EDANA|  2G  |  2G  |
+----------+------+------+------+------+------+------+------+------+------+------+------+------+------+------+------+------+------+
| CAL_NIPS | 1,00 |  ,00 |  ,01 | -,68*| -,10 | -,04 | -,34*| -,80*| -,82*| -,77*| -,00 | -,81*|  ,91*| -,67*| -,46*|  ,59*|  ,75*|
|   SAMPLE |  ,00 | 1,00 | -,24 | -,01 |  ,34*| -,11 |  ,01 | -,12 | -,07 | -,11 |  ,23 |  ,01 | -,01 | -,10 | -,12 |  ,27*|  ,07 |
| GRAMMAGE |  ,01 | -,24 | 1,00 | -,15 |  ,07 |  ,20 | -,03 | -,10 | -,08 | -,04 | -,19 | -,15 |  ,01 |  ,08 |  ,11 | -,19 | -,20 |
|     BULK | -,68*| -,01 | -,15 | 1,00 | -,07 | -,21 |  ,26 |  ,94*|  ,86*|  ,78*|  ,12 |  ,91*| -,85*|  ,72*|  ,68*| -,32*| -,22 |
| LIGHT_SC | -,10 |  ,34*|  ,07 | -,07 | 1,00 |  ,69*|  ,20 | -,09 | -,28*| -,43*|  ,78*|  ,08 | -,10 |  ,15 | -,59*|  ,49*|  ,03 |
|  OPACITY | -,04 | -,11 |  ,20 | -,21 |  ,69*| 1,00 | -,32*| -,13 | -,29*| -,41*|  ,66*|  ,05 |  ,01 | -,22 | -,47*|  ,31*|  ,01 |
| PERMEABI | -,34*|  ,01 | -,03 |  ,26 |  ,20 | -,32*| 1,00 |  ,28*|  ,22 |  ,22 | -,05 |  ,18 | -,35*|  ,78*| -,13 | -,18 | -,32*|
| BROUGHNE | -,80*| -,12 | -,10 |  ,94*| -,09 | -,13 |  ,28*| 1,00 |  ,94*|  ,87*|  ,03 |  ,94*| -,90*|  ,73*|  ,66*| -,49*| -,44*|
|    PPS_5 | -,82*| -,07 | -,08 |  ,86*| -,28*| -,29*|  ,22 |  ,94*| 1,00 |  ,98*| -,20 |  ,89*| -,90*|  ,65*|  ,77*| -,67*| -,57*|
|   PPS_10 | -,77*| -,11 | -,04 |  ,78*| -,43*| -,41*|  ,22 |  ,87*|  ,98*| 1,00 | -,40*|  ,78*| -,83*|  ,61*|  ,81*| -,75*| -,60*|
| COMP5_10 | -,00 |  ,23 | -,19 |  ,12 |  ,78*|  ,66*| -,05 |  ,03 | -,20 | -,40*| 1,00 |  ,26 | -,06 |  ,01 | -,41*|  ,65*|  ,31*|
| DELTAPPS | -,81*|  ,01 | -,15 |  ,91*|  ,08 |  ,05 |  ,18 |  ,94*|  ,89*|  ,78*|  ,26 | 1,00 | -,91*|  ,64*|  ,57*| -,37*| -,43*|
|    GLOSS |  ,91*| -,01 |  ,01 | -,85*| -,10 |  ,01 | -,35*| -,90*| -,90*| -,83*| -,06 | -,91*| 1,00 | -,77*| -,56*|  ,53*|  ,61*|
|    UNGER | -,67*| -,10 |  ,08 |  ,72*|  ,15 | -,22 |  ,78*|  ,73*|  ,65*|  ,61*|  ,01 |  ,64*| -,77*| 1,00 |  ,31*| -,38*| -,44*|
|    EDANA | -,46*| -,12 |  ,11 |  ,68*| -,59*| -,47*| -,13 |  ,66*|  ,77*|  ,81*| -,41*|  ,57*| -,56*|  ,31*| 1,00 | -,54*| -,24 |
| SO25S_2G |  ,59*|  ,27*| -,19 | -,32*|  ,49*|  ,31*| -,18 | -,49*| -,67*| -,75*|  ,65*| -,37*|  ,53*| -,38*| -,54*| 1,00 |  ,76*|
| SO60S_2G |  ,75*|  ,07 | -,20 | -,22 |  ,03 |  ,01 | -,32*| -,44*| -,57*| -,60*|  ,31*| -,43*|  ,61*| -,44*| -,24 |  ,76*| 1,00 |
+----------+------+------+------+------+------+------+------+------+------+------+------+------+------+------+------+------+------+
```

Variable specifications in the correlation table above

Short name	Specification	
cal nips	Calendering nip times	
sample	Furnish no	
grammage	Grammage	g/m^2
bulk	Bulk	cm^3/g
filler	Filler*)	%
light sc	Light scattering coefficient	m^2/kg
opacity	Opacity	%
permeabi	Bendtsen air permeability	ml/min.
Broughne	Bendtsen 98 kPa roughness	ml/min.
PPS-5	PPS S5 roughness	µm
PPS-10	PPS S10 roughness	µm
Comp5/10	PPS 5/10 compressibility	
DeltaPPS	Delta PPS compressibility	µm
Gloss	Paper gloss	%
Unger	Cobb-Unger oil absorption	g/m^2
Edana	EDANA bending stiffness	
SO25s 2g	Set-off 2,5 s at 2 g/m^2	D
SO60s 2g	Set-off 60 s at 2 g/m^2	D

5.4 Viscosity of ink vs. ink setting - Test series 4

Ink formulas for test series 4 /122/.

Ink formulas

Raw materials	**News inks Formula, composition, %**			
	1	**2**	**3**	**4**
Gilsonite varnish	25	25	25	25
Carbon black medium structured	20	20	20	20
Mineral oil high viscosity	55	45	35	25
Mineral oil low viscosity	-	10	20	30
Share of the oil blend in ink	55	55	55	55
Total	100,0	100,0	100,0	100,0

Raw materials	**News inks Formula, composition, %**			
	5	**6**	**7**	**8**
Gilsonite varnish	30	25	20	15
Carbon black medium structured	20	20	20	20
Mineral oil high viscosity	45	45	45	45
Mineral oil low viscosity	5	10	15	20
Share of the oil blend in ink	50	55	60	65
Total	100,0	100,0	100,0	100,0

Raw materials	**News inks Formula, composition, %**			
	9	**10**	**11**	**12**
Gilsonite varnish	25	25	25	25
Carbon black medium structured	20	20	20	20
Vegetable oil high viscosity	55	45	35	25
Vegetable oil low viscosity	-	10	20	30
Share of the oil blend in ink	55	55	55	55
Total	100,0	100,0	100,0	100,0

Raw materials	**News inks Formula, composition, %**			
	13	**14**	**15**	**16**
Gilsonite varnish	30	25	20	15
Carbon black medium structured	20	20	20	20
Vegetable oil high viscosity	-	-	-	-
Vegetable oil low viscosity	50	55	60	65
Share of the oil blend in ink	50	55	60	65
Total	100,0	100,0	100,0	100,0

Raw materials	**News inks Formula, composition, %**			
	17	**18**	**19**	**20**
Gilsonite varnish	20	35	35	35
Carbon black medium structured	20	20	20	20
Mineral oil high viscosity	50	-	-	-
Mineral oil low viscosity	10	45	20	-
Vegetable oil low viscosity	-	-	25	45
Share of the oil blend in ink	60	45	45	45
Total	100,0	100,0	100,0	100,0

5.5.2 Viscosity of ink vs. ink setting – Test series 4

Viscosity measurements of 20 lab inks and 1 production scale news ink. Haake RT20 results (Pas) measured at 30°C. Laray results (Pas) measured at 25°C. /122/

	Shear rate				
News inks	**50 1/s**	**100 1/s**	**500 1/s**	**1000 1/s**	**Laray**
1	37,5	32,8	20,3	13,8	19,2
2	21,2	17,5	10,8	8,1	7,1
3	12,5	10,6	6,0	4,6	3,0
4	8,8	7,1	3,7	2,7	1,6
5	29,9	25,4	15,2	10,5	13,1
6	21,6	18,8	11,1	8,3	7,1
7	16,7	14,5	8,5	6,4	5,8
8	11,7	10,3	5,9	4,7	4,0
9	37,9	28,3	13,6	9,5	7,6
10	33,2	22,8	10,2	6,6	5,0
11	35,1	19,8	7,9	5,1	2,8
12	23,4	14,5	5,6	3,5	1,4
13	13,4	9,1	3,1	1,9	0,6
14	12,7	8,8	3,0	1,8	0,5
15	9,6	6,7	2,5	1,5	0,2
16	10,3	6,6	2,5	1,5	0,3
17	34,0	29,5	16,6	10,7	16,8
18	9,4	7,0	2,9	2,0	0,6
19	8,4	6,0	2,6	1,8	0,3
20	15,3	10,7	3,6	2,3	0,2
21*	10,0	7,9	4,7	3,8	2,5

* Production ink

Prüfbau printing results for test series 4 interpolated to a constant print density 1.0 D /122/.

Inks	**Set-off 2,5 s**	**Set-off 60 s**	**Print-through**	**Strike-through**	**Show-through**	**Ink requirement**
	D	**D**	**D**	**D**	**D**	**g/m^2**
1	0,74	0,54	0,071	0,042	0,029	2,10
2	0,74	0,55	0,084	0,053	0,031	2,40
3	0,76	0,51	0,088	0,064	0,024	2,60
4	0,79	0,53	0,101	0,080	0,021	2,80
5	0,79	0,59	0,082	0,058	0,024	2,25
6	0,82	0,53	0,083	0,051	0,032	2,25
7	0,78	0,48	0,080	0,047	0,033	2,35
8	0,70	0,42	0,088	0,062	0,026	2,50
9	0,59	0,27	0,070	0,042	0,028	2,00
10	0,50	0,21	0,074	0,048	0,026	2,05
11	0,52	0,16	0,078	0,050	0,028	2,15
12	0,46	0,14	0,076	0,052	0,024	2,25
13	0,48	0,12	0,100	0,072	0,028	2,60
14	0,37	0,08	0,100	0,076	0,024	2,60
15	0,29	0,09	0,097	0,072	0,025	2,60
16	0,27	0,08	0,103	0,080	0,023	2,80
17	0,67	0,40	0,065	0,040	0,025	1,95
18	0,72	0,32	0,102	0,076	0,026	2,70
19	0,65	0,28	0,097	0,072	0,025	2,65
20	0,54	0,18	0,095	0,065	0,030	2,45
21*	0,75	0,54	0,075	0,047	0,028	2,35
Average	0,62	0,33	0,086	0,059	0,027	2,40
Std dev.	0,17	0,18	0,012	0,013	0,003	0,25
Range	0,27-0,82	0,08-0,59	0,065-0,103	0,040-0,080	0,021-0,033	1,95-2,80

* Production ink

5.5.2 Viscosity of ink vs. ink setting – Test series 4.

Variable specifications in the correlation tables for Appendix 9(4).

Short name	Specification
GILSONI	Gilsoniitti
MIN_HIGH	Share of high viscosity mineral oils
MIN_LOW	Share of low viscosity mineral oils
VEG_HIGH	Share of high viscosity vegetable oils
VEG_LOW	Share of low viscosity vegetable oils
HIGH_OIL	Share of high viscosity oils
LOW_OIL	Share of low viscosity oils
INK_REQU	Ink requirement g/m^2
SO_2_5S	Set-off after 2,5 s delay
SO_60S	Set-off after 60 s delay
DELTA_SO	Delta set-off, set-off 2,5 s minus set-off 60 s
PRINT_TH	Print through
STRIKETH	Strike through
L50_1_S	Haake viscosity 50 1/s
L100_1_S	Haake viscosity 100 1/s
H500_1_S	Haake viscosity 500 1/s
H10001_S	Haake viscosity 1000 1/s
LARAY	Laray viscosity 500 1/s
INVH100	Inverse square root of Haake viscosity 100 1/s
INVH50	Inverse square root of Haake viscosity 50 1/s
INVH1000	Inverse square root of Haake viscosity 1000 1/s

5.5.2 Viscosity of ink vs. ink setting - Test series 4.

Linear correlations of set-off vs. ink properties. 20 model inks and 1 commercial ink

Prod No	Gilsoni	Min high	Min low	Veg high	Veg low	high oil	low oil	Mobile	ink requ	SO 2,5s	SO 60s	delta SO	rel D SO	print th	striketh	L50 1/s	L100 1/s	H500 1/s	H10001/s	Laray	InvH100	InvH50	InvH1000
1	25	55				55	0	55	2,10	0,74	0,54	0,20	27,0	0,07	0,04	37,5	32,8	20,3	13,8	19,2	0,17	0,16	0,27
2	25	45	10			45	10	55	2,40	0,74	0,55	0,19	25,7	0,08	0,05	21,2	17,5	10,8	8,1	7,1	0,24	0,22	0,35
3	25	45	10			35	20	55	2,60	0,76	0,51	0,25	32,9	0,09	0,06	12,5	10,6	6,0	4,6	3,0	0,31	0,28	0,47
4	25	25	30			25	30	55	2,80	0,79	0,53	0,26	32,9	0,10	0,08	8,8	7,1	3,7	2,7	1,6	0,38	0,34	0,61
5	30	45	5			45	5	50	2,25	0,79	0,59	0,20	25,3	0,08	0,06	29,9	25,4	15,2	10,5	13,1	0,20	0,18	0,31
6	25	45	10			45	10	55	2,25	0,82	0,53	0,29	35,4	0,08	0,05	21,6	18,8	11,1	8,3	7,1	0,23	0,22	0,35
7	20	45	15			45	15	60	2,35	0,78	0,48	0,30	38,5	0,08	0,05	16,7	14,5	8,5	6,4	5,8	0,26	0,24	0,40
8	15	45	20			45	20	65	2,50	0,70	0,42	0,28	40,0	0,09	0,06	11,7	10,3	5,9	4,7	4,0	0,31	0,29	0,46
9	25			55		55	0	55	2,00	0,59	0,27	0,32	54,2	0,07	0,04	37,9	28,3	13,6	9,5	7,6	0,19	0,16	0,32
10	25			45	10	45	10	55	2,05	0,50	0,21	0,29	58,0	0,07	0,05	33,2	22,8	10,2	6,6	5,0	0,21	0,17	0,39
11	25			35	20	35	20	55	2,15	0,52	0,16	0,36	69,2	0,08	0,05	35,1	19,8	7,9	5,1	2,8	0,22	0,17	0,44
12	25			25	30	25	30	55	2,25	0,46	0,14	0,32	69,6	0,08	0,05	23,4	14,5	5,6	3,5	1,4	0,26	0,21	0,53
13	30				50	0	50	50	2,60	0,48	0,12	0,36	75,0	0,10	0,07	13,4	9,1	3,1	1,9	0,6	0,33	0,27	0,73
14	25				55	0	55	55	2,60	0,37	0,08	0,29	78,4	0,10	0,08	12,7	8,8	3,0	1,8	0,5	0,34	0,28	0,75
15	20				60	0	60	60	2,60	0,29	0,09	0,20	69,0	0,10	0,07	9,6	6,7	2,5	1,5	0,2	0,39	0,32	0,82
16	15				65	0	65	65	2,80	0,27	0,08	0,19	70,4	0,10	0,08	10,3	6,6	2,5	1,5	0,3	0,39	0,31	0,82
17	20	50	10			50	10	60	1,95	0,67	0,40	0,27	40,3	0,07	0,04	34,0	29,5	16,6	10,7	16,8	0,18	0,17	0,31
18	35		45			0	45	45	2,70	0,72	0,32	0,40	55,6	0,10	0,08	9,4	7,0	2,9	2,0	0,6	0,38	0,33	0,71
19	35		20		25	0	45	45	2,65	0,65	0,28	0,37	56,9	0,10	0,07	8,4	6,0	2,6	1,8	0,3	0,41	0,35	0,75
20	35				45	0	45	45	2,45	0,54	0,18	0,36	66,7	0,10	0,07	15,3	10,7	3,6	2,3	0,2	0,31	0,26	0,66
21									2,35	0,75	0,54	0,21	28,0	0,08	0,05	10,0	7,9	4,7	3,8	2,5	0,36	0,32	0,51

Correlations (fab inks for statsheet4.sta); Marked (non-italic) correlations are significant at p < ,05000

	GILSONI	MIN_HIGH	MIN_LOW	VEG_HIGH	VEG_LOW	HIGH_OIL	LOW_OIL	INK_REQU	SO_2_5S	SO_60S	DELTA_SO	PRINT_TH	STRIKETH	L50_1_S	L100_1_S	H500_1_S	H10001_S	LARAY	INVH100	INVH50	INVH1000
GILSONI	1,000	*-0,119*	*0,351*		-0,293	*-0,155*	*0,094*	*0,094*	*0,214*	*-0,006*	0,577	*0,238*	*0,227*	*-0,064*	*-0,096*	*-0,134*	*-0,146*	*-0,166*	*0,115*	*0,084*	*0,164*
MIN_HIGH	*-0,119*	1,000	-0,869			0,923	-0,830	-0,808	*-0,417*	*-0,168*	*-0,223*	-0,858	-0,911	0,718	0,731	0,744	0,772	0,709	-0,824	-0,796	-0,873
MIN_LOW	*0,351*	-0,869	1,000			-0,774	0,856	0,737	*-0,174*	*-0,599*	0,759	0,805	0,831	-0,743	-0,753	-0,783	-0,812	-0,727	0,806	0,795	0,829
VEG_HIGH	*0,000*			1,000	-0,971	1,000	-0,971	-0,945	*0,653*	0,839	*0,292*	-0,986	-0,939	0,972	0,980	0,976	0,966	0,944	-0,934	-0,927	-0,967
VEG_LOW	*-0,293*			-0,971	1,000	-1,000	0,959	0,874	-0,771	-0,837	*-0,514*	0,863	0,889	-0,837	-0,860	-0,874	-0,878	-0,843	0,785	0,744	0,909
HIGH_OIL	*-0,155*	0,923	-0,774	1,000	-1,000	1,000	-0,931	-0,623	*0,188*	*0,233*	*-0,276*	-0,705	-0,683	0,559	0,750	0,809	0,847	0,735	-0,727	-0,558	-0,911
LOW_OIL	*0,094*	-0,830	0,856	-0,971	0,959	-0,931	1,000	0,779	-0,687	-0,709	*0,190*	0,890	0,850	-0,762	-0,836	-0,864	-0,892	-0,767	0,876	0,770	0,985
INK_REQU	*0,094*	-0,808	0,737	-0,945	0,874	-0,623	0,779	1,000	*-0,194*	*-0,189*	*0,031*	0,931	0,908	-0,912	-0,894	-0,813	-0,789	-0,701	0,910	0,909	0,813
SO_2_5S	*0,214*	*-0,417*	*-0,174*	*0,653*	-0,771	*0,188*	-0,687	-0,194	1,000	0,934	*-0,045*	*-0,353*	*-0,357*	*0,106*	*0,274*	0,437	0,507	0,461	*-0,302*	*-0,117*	-0,630
SO_60S	*-0,006*	*-0,168*	*-0,599*	0,839	-0,837	*0,233*	-0,709	-0,189	0,934	1,000	*-0,398*	*-0,408*	*-0,388*	*0,116*	*0,317*	0,518	0,591	0,564	*-0,322*	*-0,127*	-0,664
DELTA_SO	0,577	-0,223	0,759	*0,292*	*-0,514*	*-0,276*	*0,190*	*0,031*	*-0,045*	*-0,398*	*1,000*	*0,234*	*0,169*	*-0,052*	*-0,184*	*-0,328*	*-0,353*	*-0,395*	*0,125*	*0,056*	*0,239*
PRINT_TH	*0,238*	-0,858	0,805	-0,986	0,863	-0,705	0,890	0,931	*-0,353*	*-0,408*	*0,234*	1,000	0,948	-0,854	-0,875	-0,855	-0,855	-0,751	0,891	0,850	0,908
STRIKETH	*0,227*	-0,911	0,831	-0,939	0,889	-0,683	0,850	0,908	*-0,357*	*-0,388*	*0,169*	0,948	1,000	-0,778	-0,802	-0,790	-0,799	-0,693	0,837	0,791	0,866
L50_1_S	*-0,064*	0,718	-0,743	0,972	-0,837	0,559	-0,762	-0,912	*0,106*	*0,116*	*-0,052*	-0,854	-0,778	1,000	0,957	0,856	0,817	0,734	-0,934	-0,965	-0,769
L100_1_S	*-0,096*	0,731	-0,753	0,980	-0,860	0,750	-0,836	-0,894	*0,274*	*0,317*	*-0,184*	-0,875	-0,802	0,957	1,000	0,965	0,939	0,889	-0,951	-0,928	-0,850
H500_1_S	*-0,134*	0,744	-0,783	0,976	-0,874	0,809	-0,864	-0,813	0,437	0,518	*-0,328*	-0,855	-0,790	0,856	0,965	1,000	0,994	0,966	-0,904	-0,834	-0,888
H10001_S	*-0,146*	0,772	-0,812	0,966	-0,878	0,847	-0,892	-0,789	0,507	0,591	*-0,353*	-0,855	-0,799	0,817	0,939	0,994	1,000	0,957	-0,891	-0,804	-0,915
LARAY	*-0,166*	0,709	-0,727	0,944	-0,843	0,735	-0,767	-0,701	0,461	0,564	*-0,395*	-0,751	-0,693	0,734	0,889	0,966	0,957	1,000	-0,793	-0,703	-0,807
INVH100	*0,115*	-0,824	0,806	-0,934	0,785	-0,727	0,876	0,910	*-0,302*	*-0,322*	*0,125*	0,891	0,837	-0,934	-0,951	-0,904	-0,891	-0,793	1,000	0,975	0,900
INVH50	*0,084*	-0,796	0,795	-0,927	0,744	-0,558	0,770	0,909	*-0,117*	*-0,127*	*0,056*	0,850	0,791	-0,965	-0,928	-0,834	-0,804	-0,703	0,975	1,000	0,797
INVH1000	*0,164*	-0,873	0,829	-0,967	0,909	-0,911	0,985	0,813	-0,630	-0,664	*0,239*	0,908	0,866	-0,769	-0,850	-0,888	-0,915	-0,807	0,900	0,797	1,000

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Evaluation of Ink Transfer Theory

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Keywords: Newspaper, Analysis, Ink Transfer, Blanket, Compressibility

Abstract: The ink transfer process has been a subject of interest for many years. Walker and Fetsko created an equation for the process in 1955. According to theory the three parameters controlling the ink transfer are immobilisation, splitting, and ink coverage (smoothness). Later, new equations have been developed, almost all based on the same theory. During recent years, some researchers have argued against the theory, because of correlation between the parameters. Also, some visual observations have created criticism against the theory. This study has concentrated on ink transfer in coldset offset printing using a rough uncoated newsprint surface. Some earlier results will be referred to also. During multi colour printing the earlier printed inks are influenced by subsequent ink coverage such that the first printed ink can flow readily under the surface fibres. This is not common if only one colour is printed, but the situation seems to be very sensitive to the amount and viscosity of the inks printed.

Introduction

This study is concentrated on the ink transfer mechanism in coldset web offset (CSWO) printing on relatively rough newsprint, and its simulation on the laboratory scale using a Prüfbau laboratory printing device. Generally, ink transfer in a printing nip has been discussed widely. Reviews for the item have been published (Parker 1973 published 1976, Oittinen and Lindqvist 1981, Mangin et al. 1982, Lyne and Aspler 1982, De Grace and Dalphond 1989). Ink transfer has often been presented in a form of mathematical equations. The oldest and best known equation for the ink transfer was created by Walker and Fetsko (W-F) (1955), as presented equation (1):

$$y = A[bB(1-f)+fx] \qquad (1)$$

$$A = 1 - e^{-kx}$$

$$B = 1 - e^{-x/b}$$

with

y: the ink amount on paper (g/m^2)

A: the ‘coverage function’, or the fraction of the area covered by ink

k: a 'printing smoothness' parameter (m^2/g) indicates how fast full contact is reached between the substrate and an in-creasing ink film x

B: the ‘immobilisation function’, or the fraction of the immobilised ink

b: the immobilisation capacity of the substrate under a given set of printing conditions (g/m^2)

f: the splitting factor

x the total ink amount on the printing plate or blanket (g/m^2).

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For smooth printing substrates k >0.5 and b<1, while for rough papers k <0.5 and b> 5. These figures can vary considerably depending upon ink rheology, and especially viscosity. Because A is the fraction of the area covered by ink and B is the fraction of the immobilised ink, it could be assumed that $B \leq A$. However, such a relation is not always found e.g. Chou and Tasker (1994).

As in equation (1) ink transfer is commonly divided into the following stages; coverage, immobilisation, and splitting. During splitting it is considered that the portion of ink penetrated into capillaries could 'rise away' from wider capillaries (Oittinen 1976). In addition, at the end of the splitting the compressed paper could revert to its original form thereby creating widening of capillaries which creates further ink absorption (by suction). However, penetration by aspiration after the printing nip may only be theoretical and as Oittinen and Lindqvist (1981) have noted, over that period measurements of the magnitude of the penetration have not been possible.

The mathematical parameters and related functions should describe paper properties such as smoothness and absorption. The difficulty in establishing such a relationship with paper properties has been one reason for doubting the theory. It has been found also that the parameters describing coverage, immobilisation and splitting have either been too high in variation, or the parameters inter-correlate (Mangin et al. 1982, Chou and Tasker 1994).

Evaluation of the ink transfer process has often been achieved using sheet fed offset inks and coated paper grades. Letterpress newsinks and newsprint paper grades have been used also in these studies. Today the coldset web offset printing (CSWO) method dominates newspaper printing. From the ink transfer perspective these printing processes differ from each other. Low shear viscosity, which is important for ink coverage, is much higher in the case of sheet fed inks than for CSWO, e.g. 20-50 Pas and 10-15 Pas respectively. In sheet fed offset printing, it is usual to use anti set-off powders to prevent set-off. Thus, it is possible to print with higher amount of inks to reach a required high print density. Letterpress newsinks have a lower viscosity than CSWO inks.

In letterpress printing, higher ink amounts are used because the inks are less pigmented (about 12%) compared with CSWO inks (about 20%). The higher pigmentation of CSWO inks and the higher tack and viscosity help in printing with a lower ink transfer to paper. Approximately 1.5-2 g/m^2 is sufficient for achieving the target print density. This ensures less dot gain, lower print through, and less set-off. Less than 4 g/m^2 in the printing nip is needed as the amount of ink transferred is above 50%. However, much higher ink amounts up to 25 g/m^2 have often been studied. It might not be a surprise that the ink transfer mechanism is different for lower and higher amounts of ink. It is concluded e.g. (Walker and Fetsko 1955, Chagas and Baudin 1996, and Nordstöm and Grön 1998)) that with low ink amounts, ink coverage dominates the ink transfer, followed by immobilisation, and splitting which covers the larger ink amounts.

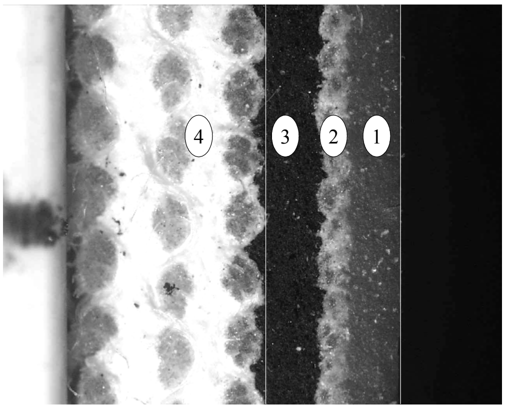
Ink transfer in CSWO printing to uncoated, rough paper

Compressible rubber blanket

For analysing ink transfer it is necessary to study the materials performance in the printing nip. Oittinen and Lindqvist (1981) have pointed out that the distribution of pressure in the nip is dependent upon the ink, the paper, and the rubber blanket. However, the overriding factor is the behaviour the rubber blanket in the input and middle of the nip. The reason is that the blanket is the most compressible material of the three.

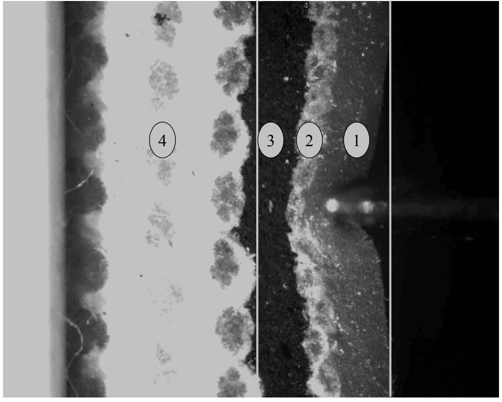
The offset blanket is not only compressible but also conformable. As an example, Figures 1-3 illustrate a range of performance behaviour for an offset blanket. Figure 1 shows an offset blanket in its original form; while Figure 2 shows the ease of deformation under the action of 50 μm wide screw driver. Figure 3 illustrates the compressive behaviour of the blanket and the resilient nature of the rubber surface under the action of a 1 mm screw driver.

Figures 1-3 illustrate that the rubber surface can accommodate a small scale roughness variation, while the compressible nature of the blanket controls the larger thickness variation of paper. The rubber can 'penetrate' into the surface voids of paper carrying ink to the surfaces located on the lower level of the roughness profile. The deepest and steepest voids avoid this penetration.



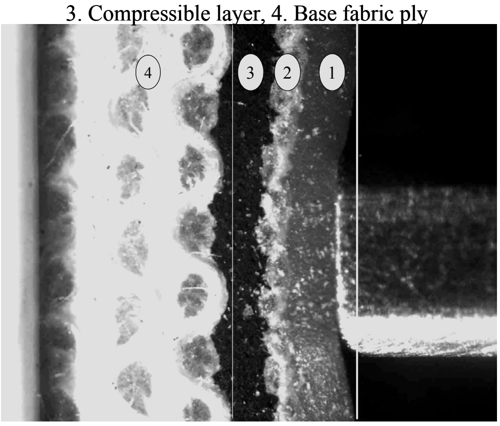
1. Surface rubber layer, 2. Stabilizing fabric ply,
3. Compressible layer, 4. Base fabric ply

Figure 1. Cross section of a compressible offset blanket.



1. Surface rubber layer, 2. Stabilizing fabric ply,
3. Compressible layer, 4. Base fabric ply

Figure 2. Cross section of a compressible blanket, with localised deformation arising from a 50 μm wide screw driver. The rubber layer is not damaged.



1. Surface rubber layer, 2. Stabilizing fabric ply,
3. Compressible layer, 4. Base fabric ply.

Figure 3. Cross section of a compressible blanket, as deformed by 1 mm wide screw driver.

In offset newspaper printing, paper, ink, and blankets enter into the printing nip with a speed of about 10 m/s at an average pressure about 2 MPa. The schematic is shown in Figure 4. The nip time duration is about 1-2 ms.

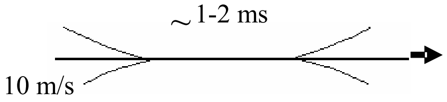


Figure 4. The elements entering the printing nip: ink, paper, and blanket.

When printing with an IGT laboratory printing press, using small ink amounts with both coated and uncoated papers Singh et al. (1996) found that the best fit for the coverage results (with $r^2 >$ 0.97) was reached using Hsu's (1962) coverage equation $A/(1-A) = kx^n$, where A is the covered area and x is thickness of the ink film on a printing form; k and n are constants which do not cross-correlate, while k correlated with roughness of the papers studied. In the same study the coverage function of the W-F equation, and that also for Karttunen's (1970) equation did not fit the printed results.

It is known that the changes taking place within the printing nip involve both movement and compression. Within this ‘violent’ regime, it is important to establish which of the elements is the weakest to respond to both movement and compression.

The easiest moving element is the printing ink, due to its liquid form. Ink can move away easily from, say the gap between a topmost fibre and blanket. Hsu (1962) has calculated the effect of paper roughness on the changes in ink film thickness within a printing nip. Also, the topmost fibres are often seen clear of ink while the ink has been seen to locate on both sides of the fibre edges. The second moving element is the rubber surface of the offset blanket. The rubber can conform to the roughness profile of paper. The surface of uncoated newsprint has a steep shape profile. That is why the rubber can not contour the profile completely, but moves towards the wider gaps and voids (width approximately 20-100 μm) located between fibres, transferring the thin ink film to the lower parts of the surface profile. In this way the less steep walls of the voids can be covered by ink.

During the nip dwell time, compression of blanket and paper takes place. The behaviour of rubber is similar to a liquid in that it maintains its volume under pressure, unlike the compressible layer and support fabric of the blanket. It is obvious therefore that the bulk of the blanket, about 2 mm thick, cannot be deformed to conform to the roughness profile. However, it can accommodate the wider areas like the thickness variation in the millimetre scale. In the area of 0.1-1 mm, there are the roughness variation of newsprint, along which both the rubber surface and the whole compressible blanket might conform.

Both the body and surface of newsprint are able to compress. The space between layered fibres contracts first when the topmost fibres transfer the pressure to the fibre matrix. The compression of fibres themselves is negligible. When the pressure against the topmost fibres increases, the fibres start to intrude into the paper body. This generates further pressure in the paper body creating movement of both fines and fibres without breaking bonds. In this way the surface becomes smoother and better contact can be reached with the ink film on the blanket.

During the time of compression of blanket and paper, and movement of the rubber surface, ink flows in the direction corresponding to the lowest counter pressure. This flow is controlled also by the viscosity of the ink. The counter pressure is mainly created by surface forces. It is also said (De Grace and Mangin 1984 and 1987) that air between the ink layer and the paper running into the nip, and especially the air in the surface voids of the paper, could also generate counter pressure preventing ink intrusion to the surface voids. On the other hand, the good air permeability of newsprint reduces the influence of air.

The ink film on the bottom of the voids has been found to be as thin as on the higher level of the roughness profile. This situation does not tell about a remarkable ink flow to the surface voids. That is why it is also concluded that the capillary spreading into offset printed newsprint paper surfaces is over-estimated in many studies (Gregersen et al. 1994).

Coverage in multi-colour printing

In newspaper printing a solid 4-colour black consists of 240-280% tonal coverage depending, inter alia, upon the level of under colour removal (UCR). The printing sequence can vary from one printing site to the other. Generally, the colour and black inks are printed on top of each other, and more ink is transferred to the paper surface than in single colour printing. The ink transfer in the first printing unit is aided by nip pressure and the surface contour of both blanket and paper. The new ink transfer to the paper surface has the ability to push the first ink further into the surface voids.

From the cross sectional images, there is clearly greater penetration with multi colours than with mono colours (Figures 5 and 6). On the other hand, we can not see the coloured inks as separate films as it appears for rotogravure 4-colour printing (wet-on-dry). In the printing nips during wet-on-wet multi-colour printing the inks appear to be ‘more or less’ mixed with each other. The portion of the ink which lays deep within the surface voids does not split further due to a lack of contact with the blanket of the subsequent printing unit. This type of ink flow to the larger surface voids is not simply the capillary penetration as caused by hydraulic pressure, but rather a mass flow caused by kinetic energy of the subsequent transferred ink.

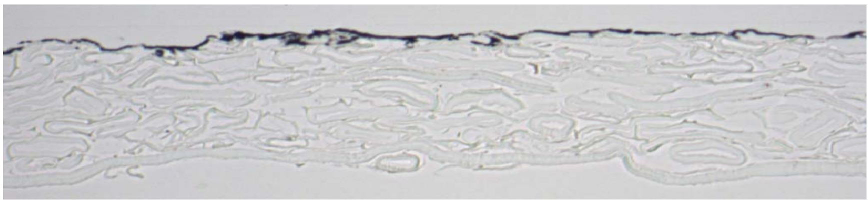
.

Figure 5. A typical picture of CSWO 1-colour newspaper printing (black)

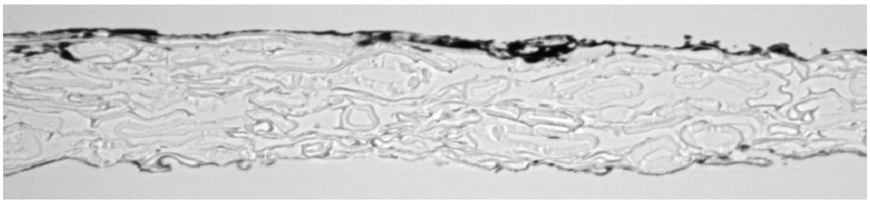


Figure 6. A typical picture of newspaper CSWO 4-colour printing.

Evaluation of the immobilisation

The immobilisation parameter of the W-F equation correlates well with the splitting factor with newsprint grades (Mangin et al. 1982), and the smoothness parameter for smooth coated grades (Chou, and Tasker 1994). In both examples the immobilisation factor could have been neglected and compensated by the other parameters. The main emphasis in the literature is that the term immobilisation is equal to penetration. However, e.g. Walker and Fetsko (1955), and also Nordström and Grön (1998) have combined it also with surface roughness.

For the case of 1.5-2 g/m^2 ink transfer to paper, roughness has a big influence on ink location on the surface of newsprint together with possibility for ink immobilisation. The high viscosity of ink prevents the penetration into smaller capillaries with insufficient ink to fill any larger surface voids (Särelä 2001). This phenomenon restricts real penetration for mono printing. However, the soft conformable rubber surface of a blanket can spread ink on a wider area via penetration to the larger surface voids. This may also increase the part of the immobilised ink.

Immobilisation in multi colour printing

During multi colour printing the first printed inks are pushed deeper into the surface voids by any subsequent printed inks, and therefore do not participate in any ink splitting. More ink can be seen under the surface fibres with some vehicle separation from the ink film taking place during the time interval between the printing units. All these processes increase the amount of immobilised ink.

Back transfer from larger voids may take place which could decrease the immobilisation of the inks (Oittinen 1976). In CSWO newspaper printing, the ink amounts are so small resulting in minimal back transfer, even for 4-colour printing.

Evaluation of splitting

Ink splitting is influenced by printing nip conditions. If a printing nip is symmetric in terms of geometry and surface properties, or both surfaces of the nip are similar with ink evenly spread on both surfaces, then ink splitting should be symmetric. However, ink splitting is seldom 50/50 between paper and blanket in practice.

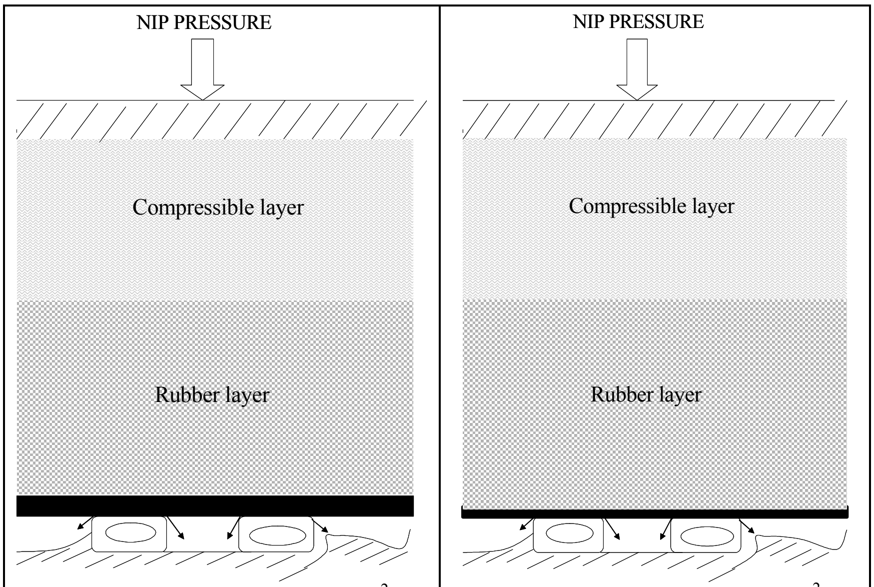
For smooth papers, the ink fraction transfer to paper is often less than 50%, compared with more than 50% for rough papers. The higher values are due to penetration of ink into the paper structure while for lower values due to smoothness of non-penetrating papers; this transfer is influenced by the counter pressure of air (De Grace and Mangin 1987).

Studies of printing blankets as a partner in ink transfer are not often published except for Chagas and Baudin (1996). However, there is considerable information in the www home pages of blanket producers. The roughness values of the blankets vary considerably between 2-12 µm whereas Ifra has proposed a value for newspaper printing of 1 µm. The difference may be symptomatic of the measuring method. However, the rough surface is able to accommodate a high share of ink compared with a smoother one.

At the end of the nip, both paper and blanket are in a compressed and conformed state. Nip pressure and the rubber blanket ensure the progression of ink to the widest possible extremity. The flattened surface of newsprint and the rubber surface of the blanket separate from each other and the ink film between them splits. As more ink film remains on the paper surface than on the rubber surface, the rubber release from the paper departs without any ink splitting taking place in a part of the transferred ink film area. Some share of the ink not in contact with the rubber surface may well progress deeper into the paper voids.

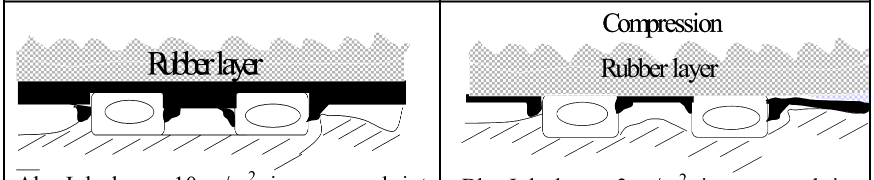
Figure 7 illustrates the ink transfer to the newsprint surface using different film weights 10 and 3 g/m^2. No compressibility has been taken into account on the left column. Instead, the pictures of the right column illustrate the impact of paper compression and conform of the blanket upon the contact between paper and ink film. Thus, during the splitting stage, more ink remains on the paper surface.

Larger surface voids (Figure 7) create non contact areas with no ink splitting. The amount of ink remaining without splitting may be smaller or larger depending upon the rheological properties of the ink. Higher speed will decrease the amount of transferred ink.



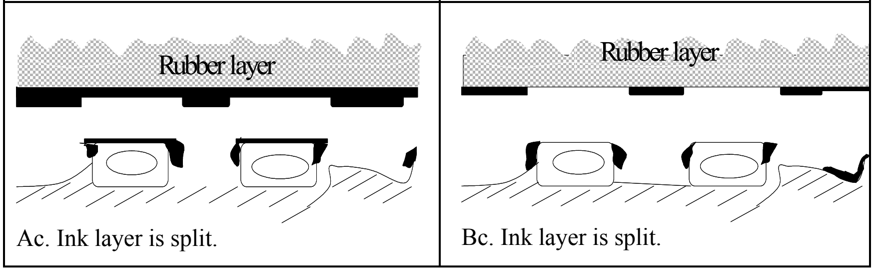
Aa. Contact between ink layer 10 g/m^2 and two fibres.

Ba. Contact between ink layer 3 g/m^2, and two fibres.



Ab. Ink layer 10 g/m^2 is squeezed into roughness profile and ink has flown away from the gap between fibre and blanket.

Bb. Ink layer 3 g/m^2 is squeezed into roughness profile and ink has flown away from the gap between fibre and blanket.



Ac. Ink layer is split.

Bc. Ink layer is split.

Figure 7. Examples of ink transfer 10 g/m^2 (left) and 3 g/m^2 (right) on the rubber blanket. On the right drawing also compressibility of the paper and conformability of the blanket have been taken into account.

Pressure distribution in a printing nip on the rough newsprint surface

The surface of newsprint for CSWO printing can be divided into both fibre and fines areas (Särelä 2001). The fibre area consists of surface fibres and is practically closed for printing ink and its components. This is because the pores of the fibre walls can be opened only upon water saturation (Maloney 2001). The fines area can be porous and is located between the surface fibres. There is often a narrow gap around the surface fibres where ink or solvent could flow (Figures 5 and 6).

Newsprint surface is rough and the roughness is inhomogeneous. Surface fibres are commonly on the higher level of the roughness profile and the fines areas form in the lower level recesses. The surface fibres located on the upper level are referred to as topmost fibres. In a test (Haapoja

2000), the surface of a newsprint sheet was compressed between a glass prism and an offset blanket. The contact picture between the class prism and the paper surface could be taken with a CCD camera, and analysed by an image analyser. When the impression pressure was increased the contact area increased also. The first contact was made with the topmost fibres with an increasing surface contact dependent upon the applied pressure. It can be assumed therefore that the topmost fibres carry the highest load of the nip pressure. Essentially the whole body compression of paper is generated by the pressure applied to these fibres with a distribution throughout all the paper fibres. The fines area and the possible hydraulic pressure applied via the thin ink layer play a minor roll in the compression of the paper. This situation explains how surface compression impacts upon the smoothening of paper in a printing nip.

Fibres normally used for newsprint production are between 20-40 µm in width. In a microscope study of newspaper printing, the topmost fibres were practically devoid of ink. The ink between the fibres and blanket was squeezed to the edges of the fibres. The non-inked area was about 20 µm wide due to the rounded nature of the fibre. Some fibres had collapsed, but not calendered flat, and had a groove in the middle of the fibre surface. The depth of the groove was found to be 2-3 µm. This groove area was normally covered with ink, but the narrow line on both sides of the groove was clear of ink. Clearly in this case, the high pressure had squeezed the ink aside. In addition, smaller areas located on the top-level of the surface profile were not covered by ink with no clear indication as to where the ink was directed. The excess ink was located somewhere around the small surface. On the other hand, there were holes or voids and cavities not covered by ink. These holes were too deep to have contact with the ink layer. Overall, the ink film on the paper surface was not continuous.

An interesting question is how high the level of pressure has to rise to clear the ink from the topmost fibres. The following chapter illustrates mathematically the impact of nip pressure upon ink transfer. For a simpler solution the situation has been approximated to that of a fibre and a smooth incompressible plate.

Flow of the ink between fibre and a plate

The flow of the incompressible liquid with constant viscosity can be described by Navier-Stokes equation (2) (Bird et al., 1960).

$$\rho \tfrac{Dv}{Dt} = -\nabla p + \mu \nabla^2 v + \rho g \qquad (2)$$

with,

ρ: density
D: substantial time derivative operator
v: velocity
t: time
∇: nabla operator
p: pressure
μ: viscosity
g: earth gravity acceleration

In order to apply this equation the physical circumstances must be clearly defined. In many cases it means that the existing geometry must be simplified and irrelevant terms be ignored from Equation (1) in order to allow the solution.

In our study the real geometry and the simplified geometry are shown in Figure 8.

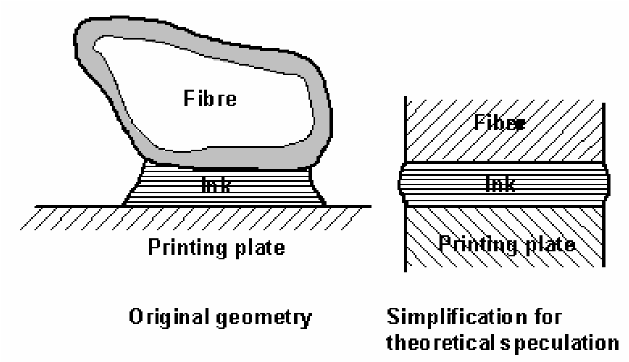


Figure 8. Schematic representation for the contact between fibre, ink and printing plate. The right hand diagram illustrates the simplified theoretical case.

The geometry of the contact between fibre, ink and printing plate is defined in Figure 9. The surfaces of printing plate and fibre are assumed to be parallel within a distance h. This space is filled by ink, which has a viscosity μ. The width of the contact zone between fibre and printing plate is 2L. The length of the contact zone is b. The fibre moves towards the printing plate at a velocity v_p.

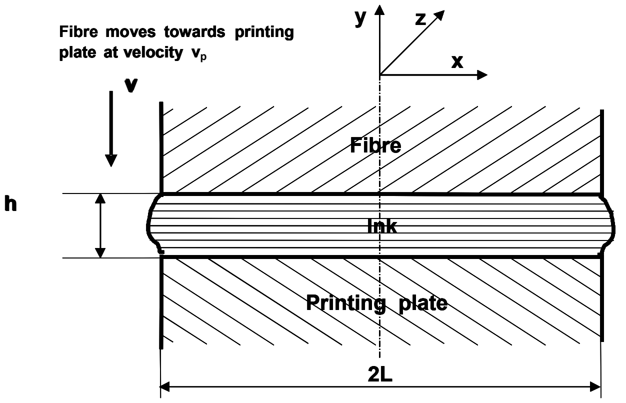


Figure 9. Definition of the geometry in contact between fibre, ink and printing plate.

The ink is compressed from the gap by the motion of the fibre towards the printing plate. The distance between fibre and printing plate is much smaller than the width of the contact area. Therefore in the theoretical speculation the influence of the flow of the ink in z-direction is ignored and the ink motion only in x-direction is considered. Navier-Stokes equation (2) for the motion in x-direction is as shown in Equation (3) (Bird, et al., 1960).

$$\rho(\frac{\partial v_x}{\partial t}+v_x\frac{\partial v_x}{\partial x}+v_y\frac{\partial v_x}{\partial y}+v_z\frac{\partial v_x}{\partial z})=-\frac{\partial p}{\partial x}+\mu(\frac{\partial^2 v_x}{\partial x^2}+\frac{\partial^2 v_x}{\partial y^2}+\frac{\partial^2 v_x}{\partial z^2})+\rho g_x \qquad (3)$$

with,
∂: partial derivative operator
x,y,z rectangular coordinates

Equation (3) is simplified further by ignoring the components caused by changes of v_x in other directions than the x-direction. The viscosity of the printing ink is high and therefore the influence of inertia forces is neglected. The effect of gravity is further ignored. This yields Equation (4).

$$\frac{\partial p}{\partial x} = \mu \frac{\partial^2 v_x}{\partial x^2} \qquad (4)$$

From Equation (4) follows the Equation (5) (Yuan, 1967).

$$\frac{\partial p}{\partial x} = -12\mu \frac{v_{av}}{h^2} \qquad (5)$$

with,
v_{av}: average ink velocity in x-direction
h: thickness of the ink layer between fibre and printing plate

Based on the continuity of mass flow, at the distance x from the centre line is valid

$$v_{av} = \frac{xbv_p}{hb} = \frac{x}{h} v_p = \frac{x}{h}\frac{dh}{dt} \qquad (6)$$

with,
b: length of the contact area of fibre and printing plate in the fibre axis' direction

By combining the Equations (5) and (6) we get Equation (7).

$$\frac{dp}{dx} = -\frac{12\mu \frac{dh}{dt}}{h^3} x \qquad (7)$$

The integration of the equation on both sides gives the pressure distribution between the fibre and printing plate.

$$p = \frac{6\mu \frac{dh}{dt}}{h^3} (L^2 - x^2) \qquad (8)$$

with,
L: half of the width of the contact area between fibre and printing plate

Because the distribution is parabolic, the mean value is 2/3 from the peak value.
The integration of the pressure over the fibre surface gives the value of the total force acting via ink between printing plate and fibre.

$$F = 2b\int_0^L p\,dx = 8\mu b \frac{dh}{dt} (\frac{L}{h})^3 \qquad (9)$$

with,
F: total force acting via ink between fibre and printing plate

Equation (9) illustrates how various factors influence the force acting between fibre and printing plate in a printing situation.

If we assume that force F is constant, we can develop Equation (9) further. By integrating the Equation (9) with respect of time we can calculate the time needed to change the thickness of the ink layer from h_1 to h_2. This is expressed in Equation (10).

$$\Delta t = \frac{4\mu b L^3}{F} (\frac{1}{h_2^2} - \frac{1}{h_1^2}) \qquad (10)$$

with,
Δt: elapsed time when the thickness of the ink layer changes from h_1 to h_2
h1: thickness of the ink layer at the beginning of the inspection period
h2: thickness of the ink layer at the end of the inspection period

Force F can be taken out from Equation (10) and it gives Equation (11).

$$F = \frac{4\mu b L^3}{\Delta t}\left(\frac{1}{h_2^2} - \frac{1}{h_1^2}\right) \tag{11}$$

Force F can be replaced by average pressure in ink and it gives Equation (12).

$$P_{av} = \frac{2\mu L^2}{\Delta t}\left(\frac{1}{h_2^2} - \frac{1}{h_1^2}\right) \tag{12}$$

with,

P_{av}: average pressure in ink layer.

Equation (8), (9), (10) (11) and (12) can be used to describe the ink-flow phenomenon between printing plate and single fibre. This helps to get a more comprehensive view of the printing process.

In the numerical examples the following values are used:
- The width of the contact surface between fibre and printing plate may vary from 10 to 40 μm.
- Length of the contact area is 0.5 mm
- The thickness of the ink layer at the beginning of the inspection period is 3 μm.
- The residence time in printing nip is app. 1 ms. As first estimate for the fibre velocity towards the printing plate it is assumed that the thickness of the ink layer approaches 0 in 1 ms. This gives the velocity 0.003 m/s.
- The viscosity of the ink is 10 Pas.

Example 1.

Pressure distribution in contact point is defined by Equation (8) and maximum value of pressure is reached when x=0. Mean pressure is 2/3 from that. Based on this equation the mean pressure is calculated and the solution is in graphical form as Figure 10.

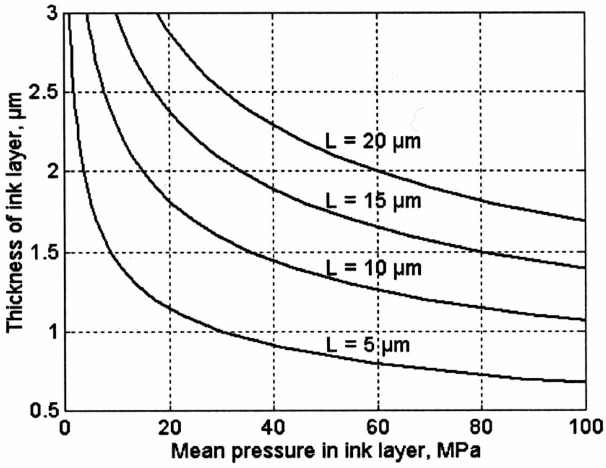


Figure 10. Mean pressure in the ink layer as function of the thickness of the ink layer. The half of the fibre width L of the contact area is a parameter. The thickness is reduced by speed 0.003 m/s.

Example 2.

Calculation of how the size of the average pressure influences on the thickness of the ink layer in printing nip.

From Equation (12) we can solve Equation (13).

$$h_2 = \sqrt{\frac{1}{\frac{P_{av} \cdot \Delta t}{2\mu L^2} + \frac{1}{h_1^2}}} \qquad (13)$$

The solution of the Equation (13) is shown in graphic form in Figure 11. We know that app. 5% of the substrate surface is in contact with printing plate in the nip. We know also that the average pressure in the printing nip is app. 2 MPa. Thus the average pressure in the contact area is app. 40 MPa. This approximation gives the situation when almost all of ink is squeezed away from the surface of a topmost fibre as often seen in the microscope pictures.

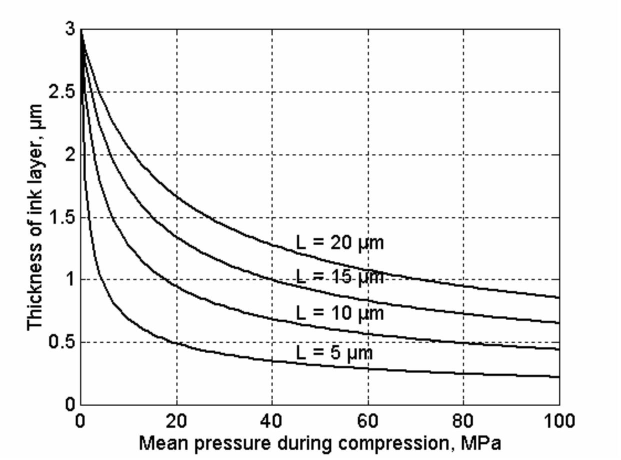


Figure 11. The thickness of ink layer as function of mean pressure during the compression. The chance happens in 1 ms. The half of the fibre width L of the contact area is as curve parameter.

Conclusions

The ink transfer within the printing nip in CSWO printing is dependent upon the properties of the printing surface; nip pressure and geometry; ink rheology and the amount on the blanket; blanket properties, and the printing speed. This is a very complex situation.

The parameter that has created confusion most towards the understanding of ink transfer is the amount of ink transfer within the printing nip. In CSWO printing, the ink film thickness is lower than with letterpress or sheet fed offset to minimise smearing. The penetration of ink within the printing nip appears to be dependent upon the ink amount on the blanket. In some cases (Gregersen et al. 1994, and Jäättelä 1996) as for mono printing, the amount of penetration was negligible. However, in this study with 4 colour printing, the ink penetration is clearly defined.

Roughness and compressibility of newsprint dominates ink transfer together with blanket properties. There is very little published work referring to the role of blankets other than within this conference.

Acknowledgements

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