Factors that affect the flexographic printability of linerboards

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ABSTRACT: *Linerboards can be printed by water-based flexography either before or after being combined with corrugated medium. Surface roughness, porosity, and water absorbency are important factors. Some common mill tests tell us little about print quality, while some nonstandard tests are more helpful. The image quality of post-printed combined boards depends on the surface properties of the liner, the structure of the fluted medium, and the effects of washboarding. Much remains inadequately quantified.*

KEYWORDS: *Bibliographies, corrugated boards, flexography, formation, linerboards, printability, print quality, surface properties, test methods, washboarding, water absorption, water based formulations, wettability.*

Corrugated boxes have long been used to pack and protect various goods. In the past, strength and durability were the major quality considerations. However, during the last two decades, the retail industry has set new demands for corrugated boxes. More and more goods are being left in the boxes in which they were shipped, to be sold directly from the shelf. To promote the product within, these boxes need graphics that are colorful and appealing with printing that is easy to read. Retailers also need clearly printed bar codes to make it more expedient to control inventory.

Corrugated board producers have recognized that the printing of boxes that were once used only for identifying the product containers has become one of the primary challenges in the manufacturing of high-quality corrugated board *(1)*. On the other hand, while there are accepted tests for measuring the strength properties of linerboard, corrugated medium, and combined board *(2)*, there are currently no commonly accepted testing methods for printability. For example, conventional wisdom holds that roughness, porosity, and water absorbency of linerboards are important for printing. However, their significance for the quality of prints on combined boards has not been established.

How do water-based inks interact with the linerboard in flexographic pre-printing? How does the presence of corrugated medium affect the interactions between ink and linerboard in post-printing? Here we review these questions in light of the current literature. We also consider the relevance and limits of some commonly used laboratory testing methods in quantifying printability properties of linerboard/corrugated boards.

FLEXOGRAPHY IN BRIEF

Water-based flexography is the dominant process for the printing of corrugated board and of other packaging materials as well *(3, 4)*. Flexography is a rotary printing method that applies fast-drying, fluid inks from a simple inking system and prints from resilient plates of rubber or photopolymer that have the image in relief.

Compared to other printing methods such as lithography or gravure, the flexo process is versatile and simple, making it preferable for print jobs that are short or medium in length. In addition, the flexible printing plates are able to contact the rough surfaces of corrugated board under relatively low pressure, which is important for minimizing the strength loss of the boards. On the other hand, simplicity and flexibility have also limited the quality of flexo printing. Often, the deformation of printing plates has caused image distortion, and the consistency of ink color has been poor because of poor ink control.

However, flexographic technology has been improved remarkably during the past decade *(3–5)*. The widespread use of chambered doctor blades and laser-engraved ceramic anilox rolls has resulted in ink metering systems that accurately control ink transfer, thus ensuring color consistency. The development of thinner plates backed with compressible cushioning materials has resulted in a reduction of plate distortion, thus improving dot fidelity. Also, advances in water-based acrylic resins, either in solution or emulsion, have led to high color strength and high gloss in water-based flexo inks. It is now claimed that a flexo press can produce prints that rival lithography or gravure in quality, while the costs are much lower *(3, 4)*.

Criteria for print quality on corrugated board

As with images printed on papers, the judgement of the quality of images printed on corrugated board is largely a subjective matter *(6)*. On the other hand, perceptual print quality is influenced by objective characteristics such as print density and print uniformity, which are in turn influenced by interactions between the inks and the liners.

When different observers judge the quality of a print, each may emphasize the influence of different factors, depending on individual experience and expectations *(6, 7)*. To determine the relative importance of the factors, we need a systematic multidimensional scaling study. Currently, however, there are no commonly accepted criteria for evaluating the print quality of corrugated boards.

Here, we attempt to identify linerboard properties that are important for flexographic printability. We assume that the subjective print quality of corrugated board is mainly affected by print density, print uniformity, print gloss, and image fidelity.

Print density

One of the primary requirements of print quality is sufficient contrast between the printed image and the substrate background. Print density is defined as the difference in optical density between a printed image and the unprinted substrate. It is a measure of this absolute contrast.

Print density is important for the quality of images printed on all substrates, including printed linerboards *(8–13)*. Ideally, a corrugated board should produce images with the desired print density with the lowest possible printing pressure, the so-called "kiss impression" condition. Otherwise, converters and printers may have to increase printing pressure to enhance ink transfer, which could cause image distortion and could also damage the fluted structure.

Print uniformity

Print uniformity *(8–10, 12, 14, 15)* pertains to evenness in optical density and printed ink gloss, both of which are important factors. Using multidimensional scaling, Lyne demonstrated that print uniformity is the most important factor in determining perceptual print quality for letterpress newspapers *(6)*. For offset *(16)* and flexo *(17)* newsprints, mottle was an important quality factor, though it was not the dominant factor. In the subjective evaluation of preprinted linerboards, Wågberg noticed that observers reacted strongly toward print mottling *(18)*.

Print gloss

Print gloss *(9, 12, 13, 15)* is the attribute of an ink film surface that causes it to be shiny, or lustrous. Ionides and Harris suggested that print gloss and paper brightness may be the only primary printability parameters that are related to market value for different grades of mechanical pulp printing papers *(19)*. For corrugated boards, since retailers want strong color and high-gloss graphics on the boxes to maximize the visual impact on the buyers, print gloss may become one of the major parameters in determining the market value of different boards.

Image fidelity

We use the term "image fidelity" to describe the difference in shape and in size between images on the printing plate and those printed on the substrate. These images include halftone dots and solid bars.

Dot gain is the increase in the size of dots from the plate to the printed sheet. Dot gain is caused by both optical spreading and physical spreading and can be detrimental to the print quality of flexography *(3, 4)*. As dot gain increases, the relative contrast of the printed images decreases, which means that the print loses its sharpness of detail.

Similarly, controlling the bar width is essential for the print quality of bar codes.

Other factors

High-quality prints should be clean and free of dirt spots caused by ink smearing or plate filling-in. The prints should be free of defects such

I. Brightness of different grades of linerboards

Grade	ISO brightness, %	Ref.
Coated bleached	≈ 88	12
Coated white top	74–82	11, 12
Bleached kraft	80–88	3, 11
White top	65–78	10, 11
Mottle white	50–65	3, 10
Unbleached kraft	15– ?*	3, 9, 10

*The ISO brightness of typical unbleached kraft liners is about 20% *(3)*.

II. Standard flute sizes of corrugated medium *(60)*

Type of flutes	Height of flutes, mm	Number of flutes/m	Take-up factor*
A	4.76	111 ± 9	1.54
B	2.38	158 ± 9	1.33
C	3.57	131 ± 9	1.45
E	1.19	303 ± 12	1.26
F	0.80	404 ± 15	...

*The ratio of the medium length before corrugation to that after flute formation.

as halos and striations. A "halo" is an undesirable peripheral outline around a printed image, and a striation is a streaky pattern of parallel lines caused by uneven inking across the web. Proper register (alignment) of two or more images is essential for print quality in multicolor processes.

Preprinting of linerboard

Regular corrugated board is made by adhering one fluted medium between two flat linerboards *(2)*. In flexo preprinting of linerboard, a web of the outer linerboard is first printed from a reel, and the reel is rewound before the printed linerboard is used in converting to make the combined board, or corrugated board. Preprinting on the smooth surface of the linerboard provides higher print quality and more consistent color intensity than does printing on the combined board *(4)*.

Linerboards for preprint may also be lighter in basis weight than those that are printed after being glued to the corrugated medium. The lighter basis weights will still serve to produce boxes that meet a given strength requirement, since the fluted structure of the corrugated board is not weakened by printing pressure. However, the preprinted images must be stable against heat, moisture, and compression to avoid distortion and damage when the preprinted liner is glued to the corrugated medium. Currently, preprinting is justified only for long print runs, mainly because of the initial cost and the cost of waste involved for the setup of both the printing press and the corrugator.

Linerboard as printing substrate

In both the preprinting of linerboard and the post-printing of corrugated board, the physical characteristics of the printed images are determined by interactions between the ink and the liner. The linerboard properties commonly held to affect the characteristics of the prints are brightness and shade, roughness, porosity, and water absorbency *(20)*.

Brightness and shade

Brightness and shade are important in determining print quality. These two aspects of the linerboard affect the optical density and the contrast of the prints.

In the corrugated industry, brightness is the primary factor in classifying different grades of linerboards (**Table I**). In general, a whiter linerboard gives better color reproduction in halftone prints and stronger colors in solid prints *(9, 20)*. Under given printing conditions, the print contrast also increases linearly with increasing brightness of the liner *(9)*.

Brightness is important particularly for the print quality of bar codes *(21)*. A scanner reads a barcode from the difference in the reflectance between the space, or the unprinted background, and the printed bar. If the reflectance of the unprinted liner surface is not high enough, a scanner may be unable to distinguish the printed bar from the background. The Uniform Code Council (UCC) specification requires a minimum reflectance of 31.6% for the printing of UPC (Uniform Product Code) symbols. However, the brightness is lower than this minimum requirement for most linerboard in the grade of unbleached kraft (Table I) *(21)*.

Brightness refers only to the reflectance value of a liner at a specific wavelength (457 nm). It does not pertain to distinguishing color or shade. For proper color matching, it is necessary to control both the brightness and the color of the linerboards *(4, 9, 20)*.

Surface smoothness or roughness

Surface roughness or smoothness affects ink transfer and print evenness. It takes a smooth surface to receive a uniform film of ink from the printing plate *(22, 23)*.

Roughness may be defined as the deviation of a surface from an ideal smooth flatness. However, for porous materials such as paper and linerboard, there is no natural distinction between recesses and pores *(24)*. Recesses constitute roughness, but pores do not. It is difficult to define clearly and to measure accurately the surface roughness of papers. Usually printability is used as the ultimate criterion for determining the surface roughness of paper products.

In routine laboratory printability tests, the surface roughness of printing paper is often estimated from air flow rates between the paper surface and a reference plane. The most widely used devices in North America are the Sheffield, Parker Print-Surf (PPS), and Bendtsen air leak testers. The Bekk tester is also widely used in Europe. For newsprints, Bichard recently investigated the interrelationships of roughness values obtained with these different instruments. He confirmed that each method is suited to distinguish best between papers that fall within its unique range of sensitivity to roughness. Nevertheless, the roughness values estimated from different tests bear functional relationships to the values measured by other tests for a given group of papers *(25)*.

The Sheffield, Parker-Print Surf, and Bendtsen testers have been used for characterizing surface roughness of linerboards because they are quick and easy to use. Air leak roughness also correlates with flexographic printability. Such a correlation was obtained with the PPS tester, which was found to be better, however, at predicting the letterpress printability *(26)* and the rotogravure printability *(27)* of papers.

In the flexo preprinting of coated white linerboards, the print pressure needed to achieve a uniform solid print increased linearly with increasing Parker Print-Surf roughness, as measured by Jensen at a clamping pressure of 5 kg/m^2 *(12)*. Jensen also found that under constant printing conditions the optical density of a solid print decreased with increasing PPS roughness, measured at a pressure of 10 kg/m^2. Similarly, for uncoated boards, Ginman and Tiainen found that the PPS S10 roughness was a fairly good predictor for the unevenness of printed halftone areas *(8)*. Note that the PPS roughness of many uncoated linerboards is greater than 7µm, while the normal working range of the instrument is between 0.6 µm and 6 µm, according to the International Standard ISO 8791-4:1992(E), Part 4: Print-surf method.

The Bendtsen test, as described in SCAN standard P21:67 (CPPA Useful Method D.15U), appears to be the most widely used method for characterizing surface roughness of liners *(8–12, 18)*. Haglund found that unevenness of prints on uncoated liners increased with increasing Bendtsen roughness value *(9)*. Jensen reported similar results with coated liners and attributed the correlation between mottling tendency and the Bendtsen roughness to the local variations in pressure in the printing nip *(12)*. The higher areas of the liner give a higher nip impression, causing increased spreading of halftone dots and characters *(12)*. Ginman and Tiainen *(8)* as well as Pommice and coworkers *(10)* found increased dot gain with increased Bendtsen roughness. Pinholes, a highly noticeable form of print mottle, may also form in the valleys, since no ink can be transferred to the noncontact areas *(23)*.

Wågberg compared the capabilities of the PPS and Bendtsen tests in predicting flexographic printability for uncoated linerboards covering wide ranges of brightness and surface roughness *(18)*. She found that the perceptual print quality correlated with PPS roughness (with a coefficient of linear determination $R^2 = 0.75$) as well as it did with Bendtsen roughness. The PPS roughness is derived as a cube-root-mean-cube value of the air flow rate, whereas Bendtsen roughness is usually expressed as air flow rate. However, if the Bendtsen roughness is also expressed as a cube root function of the flow rate, the correlation becomes much better for the Bendtsen test ($R^2 = 0.86$) than that for the Parker Print-Surf test.

Wågberg found that the Bendtsen tester is not sensitive to small-scale variations (as determined with an optical profile tester), because it has a relatively wide metering land (0.15 mm wide). Nevertheless, the test is a good indication of the long wave variation of the boards (1–5 mm). In contrast to the Bendtsen roughness test, there is not a very strong correlation between the PPS roughness and variations of any given range of wavelength. However, the PPS tester is reasonably sensitive to linerboard structures over the full range of wavelength. The PPS tester is especially superior to the Bendtsen for characterizing the small-scale variations, because it has a smaller metering land (0.05 mm wide).

By analyzing correlations between the overall perceptual print quality and the roughness profiles determined with the optical profile tester, Wågberg also found that observers are very sensitive to surface irregularities in two different ranges of wavelength, 0.08–0.16 mm and 1–5 mm *(18)*. Variations in the range of longer wavelength had a greater influence on the subjective evaluation. Whereas the PPS tester is sensitive to variations at all wavelengths, the Bendtsen tester is nevertheless superior in determining variations in the range of longer wavelength (1–5 mm), and these variations have greater effect on the subjective print quality than do the short-range variations. Jensen suggested that the visually important print unevenness may have a range of longer wavelengths—between 3 and 9 mm *(12)*.

While the Bendtsen and PPS testers are useful in predicting the flexographic printability of linerboards, the Sheffield tester may or may not be relevant to flexographic printability. The Sheffield tester is used by many paperboard mills and is the sole TAPPI and CPPA test method for the smoothness of both paper and paperboard (TAPPI T 538 om-88 and CPPA Standard D.29). In an early study of letterpress printability of linerboards, Fetsko reported that a Sheffield tester ranked the samples as well as did a Bendtsen tester, despite the fact that the roughness range obtained with the Sheffield was much more narrow than that obtained with the Bendtsen *(15)*. However, one group of researchers recently claimed that the Sheffield test bore little relevance to the flexo printability *(14)*. They found that for bleached linerboards with very different print quality properties, the Sheffield roughness values fell within a narrow range, from 244 to 321 cm^3/min. One explanation for the failure of the Sheffield method is that its metering land is too wide (approximately 0.35 mm), which limits its sensitivity to the fine structure of the linerboard surface *(14)*.

Smoothness is necessary for high print quality, but printability is a function of many other properties as well, including porosity and absorbency. Consequently, linerboards of similar surface roughness as determined by one type of air leak instrument may produce prints of different quality *(14)*.

Porosity and air permeability

Porosity and pore size distribution influence the print quality of linerboards as a result of the effects they have on ink setting and ink holdout *(20)*. The setting of the ink and ink holdout in turn affect print density, ink gloss, and print uniformity *(28)*. Porosity is theoretically defined as the ratio of the void volume within a porous material to its total volume. However, air permeability, which is the rate at which air passes through the paper under specific conditions, has been widely used in the paper and paperboard industry as the measure of porosity *(29)*.

Air leak instruments for characterizing surface roughness have also been used for measuring air permeability. For mechanical pulp printing papers, Dalphond and Koller found that the agreement between the Gurley, Parker Print-Surf, and Sheffield testers is fairly good *(29)*. However, for unknown reasons, correlations between the Bendtsen tester and the other three devices are not so good *(29)*.

For linerboards, Steadman and coworkers measured the air permeabilities of seven bleached liners using the Bendtsen and PPS testers *(14)*. While the Bendtsen tester ranked the seven samples in the same order as did the PPS tester, the air permeability correlated poorly with print quality properties. Other researchers who reported air permeabilities of linerboards either failed to find correlations between porosity and printability or did not attempt to find these correlations *(8, 10, 11)*.

The lack of a simple correlation between air permeability and flexo printability is not a surprise. Air permeability depends not only on porosity but also on the thickness of the linerboards. Two linerboards with similar air permeabilities may have different porosities if one liner is thicker than the other. For linerboards with similar thicknesses, air permeability is a measure of porosity and pore size distribution.

Porosity is desirable because it allows the liquid ink to set quickly to avoid set-off and smearing. However, excessive porosity may cause too much ink to be imbibed into the linerboard, leaving dull ink films on the liner surface. In addition, while porosity is important for ink absorption, there are many other factors that influence capillary imbibition, as described by a modified Lucas–Washburn equation *(30)*:

$$V = (e/t)\,[(R \cdot g \cdot t \cdot \cos q)/2h]^{1/2} \quad (1)$$

where

- V = volume of liquid absorbed per unit area of linerboard surface
- e = porosity
- t = tortuosity of the porous structure
- R = average pore radius
- q = contact angle between the fiber and the ink
- g = surface tension of the ink
- h = ink viscosity
- t = penetration time.

From Eq. 1, we see that the penetration of inks into different linerboards with the same porosity may vary significantly, depending especially on the surface tension of the ink and the fiber, which determine the contact angle q. If the contact angle is larger than 90°, the ink may even be unable to penetrate the liner by capillary suction.

Equation 1 also points out that ink absorption is a function of both porosity e and average pore radius *R*. Ink holdout is primarily affected by the size of the surface pores *(31)*. If the pore size of the linerboard surface is comparable to that of ink pigment particles, the ink pigment particles will mainly be filtered out, depositing on the liner surface.

The porosity distribution is important for print uniformity. Inks on dense areas may set too slowly, causing smearing and the spreading of dots. Inks on bulky areas may drain excessively into the sheet, resulting in low print density and low gloss. Taken together, the areas of different porosity may lead to both print density mottle and gloss mottle.

The absorption of aqueous flexo inks in the printing of papers and paperboards involves not only capillary imbibition, as described by the Lucas–Washburn equation, but also other penetration mechanisms such as surface diffusion and the absorption of water by the cellulose fibers *(32, 33)*. That is, while Eq. 1 is of qualitative interest, it is unsuitable to quantitatively predict the transfer and setting of water-based inks on linerboards.

WATER ABSORBENCY

Linerboards are printed with water-based flexo inks, so water absorbency properties of the liners are important for the transfer and setting of inks. For water-based flexo newsprint, conflicting suggestions have been made on whether more *(34)* or less *(35)* absorbency is desirable. This conflict indicates that absorbency properties, as with porosity, affect print quality in a complex manner. At given printing conditions, more ink is transferred to those newsprints that are more absorbent, leading to higher print density *(36)*. However, for a given amount of ink on paper, the print density decreases with increasing water absorbency *(36)*. In other words, as a result of increased ink penetration, the "printing efficiency," or the print density per gram of ink on paper, is lower for more absorbent papers.

Cobb and IGT tests. The effect of water absorbency on the printability of linerboards has also been studied. Steadman and coworkers characterized the water absorbency of bleached linerboards with the Cobb test (TAPPI T 441 om-90 and CPPA Standard F.2) and the IGT absorption test *(14)*. They found that the Cobb test provides little or no useful information about flexo printability although it offers a good indication of the degree of sizing.

The IGT absorbency test, which measures a combined effect of surface roughness, porosity, and surface chemistry on water absorbency, gives a good correlation (R^2 = 0.85) with print density *(14)*. This test is performed by applying a known volume of flexographic ink diluted with water to the linerboard surface with a disc. The length of the ink stain is an indicator of ink holdout *(14)*. The print density increases as the stain length increases, which indicates that the liner absorbs less water. Wågberg also found a correlation (R^2 = 0.70) between the overall perceptual print quality and the IGT absorption results, using colored water as the testing liquid *(18)*. She even found a significant correlation (R^2 = 0.67) between flexographic print quality and ink transfer data with a paste offset ink, despite the fact that flexographic inks are much less viscous.

Pommice *et al.* *(10)* and Gervason and Jayet *(11)* also reported, without specifying the types of inks, that the IGT ink transfer data ranked different linerboards in the same order as in commercial printing. Thus, although it is not a standard method, the IGT test appears to have promise in predicting the flexo printability of linerboard. However, the published data are still not sufficient to conclude that the IGT test is a good predictor of flexographic printability. In addition, Steadman and colleagues reported that with the commercially available flexo printing attachment, the IGT printability tester was unable to print samples with grammages higher than 80 g/m² *(14)*.

The relevance of the Cobb absorption test in predicting flexo printability is not only a problem with uncoated linerboards. In his study of the flexographic preprinting of coated linerboards, Jensen found that the print mottle index decreased with increasing water absorbency, as determined by the STFI absorption test at a contact time of 0.45 s *(12)*. However, an analysis of his data reveals a poorer correlation between the Cobb absorbency values and his print mottle index.

Bristow tester. Wågberg also characterized the water absorbency of uncoated linerboards with the Bristow tester *(18)*. She used a modified form of Eq. 1 proposed by Bristow *(37)*, invoking the "wetting delay" to describe the absorption phenomena:

$$V = K_r + K_a\,(t - t_w)^{1/2} \qquad (2)$$

where

V = amount of liquid transferred to the linerboard

t = contact time, or absorption time

t_w = time of "wetting delay"

K_r = roughness index

K_a = absorption coefficient.

The roughness index K_r correlates well with the Bendtsen roughness. It may represent the amount of water required to fill up the surface pores before capillary imbibition occurs. The absorption coefficient K_a is the slope of the linear portion of the curve after the initial wetting delay. The "wetting delay" is still a disputed concept.

Wågberg found that the perceptual print quality correlates to a certain extent with both K_r and t_w with R^2 values of 0.61 and 0.51 respectively. However, no correlation (R^2 = 0.02) was found between the print quality and K_a.

The relationships between the flexo print quality and the values of K_r and t_w are difficult to understand, since the physical meanings of these parameters are not clear *(18)*. If we assume that the printability is mainly associated with the water absorbency at short contact times, Wågberg's results might be explained as follows.

The IGT absorption test is useful in predicting the flexo print quality because the test is performed at speeds close to those of commercial printing processes. The correlation between the IGT test and the print quality might even be higher if the IGT test were run with an aqueous solution having the surface tension and viscosity of a typical flexographic ink.

Similarly, the parameters K_r and t_w from the Bristow test, which are associated with the short-time absorption phenomena, would correlate to a certain degree with flexo printability. The reason is that the contact times between inks on the plate and the liner surface in a commercial printing nip are also very short.

On the other hand, absorbency properties for longer times, such as those determined from the Cobb test and the factor K_a from the Bristow test, may have little or no effect on the printability. The ink films applied to the linerboard surface in commercial printing usually range from 10 µm to 20 µm. Thus, water absorbency properties determined at longer contact times (a condition that in theory would make more than enough water available for penetration) would be less relevant to the print quality.

Coated vs. uncoated linerboards. The effects of water absorbency on flexo printability are also different for coated and uncoated linerboards. Low absorbency appears to lead to improved print quality for uncoated liners *(8, 14, 18)*. However, for coated liners, high absorbency seems to produce less mottling *(12)*.

Different mechanisms may be responsible for ink transfer and ink holdout for coated and uncoated papers *(31)*. For uncoated papers, the entire ink (including the ink pigment) may penetrate into the large pores of cellulose fibers. Therefore, decreasing water absorbency is helpful for improving ink holdout. Interestingly, reducing the water absorption of uncoated papers by sizing leads to improved printing for other water-based inks such as ink-jet *(38)* and water-based gravure *(39)* inks.

On the other hand, for coated papers, the ink pigment particles are largely filtered out. These particles deposit on the coating surface, since the capillary size of the coating is comparable to that of the ink pigment particles *(31)*. Therefore, further decreases in the absorbency of coated liners may have little or no effect on ink holdout. Instead, the effect may be to increase the time needed for the liquid inks to set, which may in turn increase dot spreading and mottling *(12)*.

WETTABILITY AND SURFACE CHEMISTRY

The wetting of paper surface by inks is one of the basic requirements for ink absorption and ink transfer. However, this requirement is often overlooked, since wettability has rarely been a problem with conventional oil- and solvent-based inks.

The surface tensions for these conventional inks (about 30 mN/m) are inherently lower than those of most papers. For example, using the inverse gas chromatographic technique *(40)*, Borch found that the dispersion component of the surface energy ranges from 36 mN/m for papers sized with alkyl ketene dimer to 50 mN/m for Whatman papers *(41)*. On the other hand, the surface tension of water is 72 mN/m. Classical surface chemistry theory states that a liquid will spread spontaneously only on solids that have a surface tension higher than that of the liquid *(42)*. Consequently, the wetting of papers by water is often "delayed" *(37, 43)*.

The equilibrium surface tensions of water-based flexo inks, ranging from 20 mN/m to 40 mN/m *(44, 45)*, are much lower than that of water. This difference exists because the water-based inks contain surfactants and cosolvents such as alcohols. However, Inoue and coworkers found from contact angle measurements that the surface energies of linerboards are comparable to those of these inks, ranging from 23 mN/m for unbleached recycled liners to 51 mN/m for virgin kraft linerboards *(46)*.

In addition, Bassemir and Krishnan found that the print quality is more closely related to the dynamic surface tension *(47)*. The dynamic surface tension of water-based inks is usually much higher than the equilibrium value because of the time needed for the surfactants to diffuse to the newly created surfaces. These researchers compared inks of similar, low-equilibrium surface tensions (lower than 30 mN/m). They found that print quality on a linerboard with a surface tension of 37.7 mN/m was very poor for an ink having a dynamic surface tension of 40 mN/m, at a time of 0.2 s. Aspler and colleagues also found that prints with water-based inks on hard-sized kraft handsheets were less uniform than prints on absorbent samples *(36)*. They attributed the mottling either to poor ink transfer during printing or to dewetting of the ink films on the low-energy surfaces after the inks were deposited.

While wetting is essential for the transfer of water-based inks, excessive spreading leads to increased ink penetration and dot gain. As a result, linerboards are often internally and/or surface sized. In addition, ink formulations can be modified to make it possible to print linerboards with either high, moderate, or low degrees of sizing *(20)*. However, the surface wettability may vary nonuniformly because of uneven distribution of materials such as sizing agents and waxes and adhesives from recycled fibers. This kind of local variation in wettability may lead to pronounced print mottle in addition to the mottle caused by roughness and uneven porosity distribution.

For the wettability of papers and paperboards, there are standard tests such as the Hercules size test (TAPPI T 530 pm-89) and the contact angle method (TAPPI method T 458 om-89 and CPPA Method F.3H). The Wilhelmy method *(48)* and Bristow tester *(49)* have also been used for characterizing the acid–base characteristics of the paper surface. However, these tests usually yield information about the average level of sizing. While this information may be useful in predicting the compatibility between inks and linerboards, it is unsuitable for predicting the print mottle caused by local variations in surface wettability.

Another simple test, described by CPPA Useful Method F.1U, involves the application of a drop of a model aqueous ink made from a blue acid dye dissolved in water. The uniformity in surface wettability is then visually examined from the shade of the ink streak. This method may yield qualitative information about the wetting uniformity of the surfaces if the linerboards have similar profiles for surface roughness. However, no data were published about correlations between the nonuniformity of the model ink stain and printed flexo mottle.

THE EFFECT OF pH

Water-based flexo inks are generally formulated with resins such as acrylic, fumaric, and maleic rosin esters. These resins are fairly insoluble under acidic conditions but are soluble in water under alkaline conditions *(3, 4, 50)*. Currently, ammonia and alkanolamines of low molecular weight are the most commonly used solubilizing agents. As the alkaline material evaporates from the ink, the resins become insoluble, and a water-resistant film forms on the surface.

The fact that water-based inks are alkaline, with a normal pH range of 8.0–9.0, also suggests that the pH of linerboards may affect printability. The acidity of linerboards may serve to neutralize the solubilizing amines, with the linerboard pH acting in effect as a drying agent. This effect may be desirable to avoid setoff in high-speed multicolor printing, in which a second color is printed within a fraction of a second. However, drying that takes place too fast may lead to the rapid development of tack in the ink films, causing linting and picking. In a study of the contribution of newsprint to the filling-in of flexographic plates, plate plugging was found to be influenced both by the propensity toward linting and by the interactions between the alkaline ink and the acid newspaper *(51)*. Similar interactions may occur in the flexo printing of uncoated linerboard, although none have been reported specifically.

For printing papers, the influence of acidity on the transfer and setting of inks has been reported in both water-based flexographic *(36)* and water-based gravure printing *(52)*. Aspler and coworkers found that more ink (which is alkaline) is transferred to acidic surfaces *(36)*. However, acidity has little or no effect on ink penetration. On the other hand, others have shown that alkaline water-based gravure inks set faster on acidic papers *(52)*. This apparent contradiction likely results from the thinner ink films printed on flexographic newsprints, which are about 2 μm per color. For these, the setting of ink may be dominated by the evaporation of amines or of water *(36)*. The ink films printed by gravure are about 6–8 μm per color, and both the evaporation and neutralization of the amines by paper acidity may affect the setting of ink.

Ink films applied in flexographic packaging are thicker than those applied in flexographic newsprint, ranging from 10 μm to 20 μm *(4)*. Therefore, the acid–base interactions between the ink and linerboard may play a role in ink setting, especially when a less volatile amine is used as the solubilizing agent.

THE EFFECT OF FORMATION

Formation refers to the uniformity of distribution of fibers and fillers in a sheet of paper or of paperboard. Formation is one of the most important structural properties of paper products. It affects both the average value and the degree of variation of nearly all other characteristics, including strength and printing properties *(53)*.

The effect of formation on the flexo print quality of linerboards has not been quantified. For printing papers, however, formation strongly affects the image quality printed in both offset and rotogravure processes *(27, 53, 54)*. For uncoated newsprints, Rutland and Heintze suggested that formation determines micro-roughness and the uniformity of the sheet macro-roughness *(27)*. The macro-roughness could be determined with air-leak instruments, such as the Bendtsen tester. The formation-related micro-roughness is relatively independent of air-leak roughness. However, the effect of the microroughness on gravure print quality is as important as air-leak roughness *(27)*. Formation also affects the uniformity of all printability properties, including opacity, porosity, and absorbency.

Formation also differs from some other printability properties in that it can hardly be improved by other treatments once the sheet is formed. For example, the surface smoothness of a sheet can be markedly improved with calendering. However, Kajanto *(54)* showed that with hard nip calendering the offset print mottle increased or remained unaffected. By contrast, soft nip calendering may partly compensate for the effect of formation on print mottling, because the soft nip follows to some extent the topography of the paper.

Similarly, coating cannot cover up the poor formation of a paper or paperboard. As a striking example, the print mottle of lightweight coated papers depends on the formation of the base sheet. For these papers, the sheet formation affects both the pick-up of coating color and the formation of the coating structure *(55)*. While printability properties may be enhanced to a certain extent without improving formation, it is essential to optimize the sheet formation if we expect to achieve the best possible print quality *(56–58)*.

There are various instruments for characterizing the formation of paper and paperboard *(53, 56, 59)*. However, there is no standard formation tester *(20, 59)*. A simple method of assessing formation is to visually judge a sheet by holding it up to a light. The formation is poor or wild if the fibers are unevenly distributed, and this uneven formation gives the sheet a mottled or cloudy appearance in transmitted light.

To quantify the local variation in grammage of linerboards, Kiviranta and Paulapuro used the Ambertec formation tester, which is based on the measurement of direct beta radiation *(56)*. They also applied the M/K formation tester, which is based on light transmission, to characterize the sizes and areas of fiber flocs. However, the researchers did not compare these formation measurements with printing tests. Other instrument methods for evaluating formation can be found in a recent review by Norman *(53)*.

Post printing of combined board

Corrugated post printing is a sheet-fed process that dominates the printing of corrugated containers. It is the practical, cost-effective process for short and medium-length print jobs *(4)*. However, the direct printing of combined boards is considered to be the low end of the corrugated container market.

The quality of post-printing is limited by poor register, mainly as a result of press configuration, and by the rough surface of corrugated boards, primarily because of the washboarding problem. In addition, the control of printing pressure is critical. Insufficient pressure causes poor ink transfer, which results in low print density. Excess pressure causes halos around prints and a loss of paperboard strength as a consequence of crushing the fluted structure. Local variations in printing pressure are inevitable when washboarding occurs.

On the other hand, more and more box users are looking for higher quality graphics in smaller orders. Their purpose is to promote specific products that cannot justify the extra cost of preprinted linerboard. Therefore, the manufacture of flat combined boards that can be printed without washboarding is becoming important for producers of corrugated containers.

Washboarding

Washboarding is the major substrate defect that limits the print quality of corrugated boards. In washboarding, the surface of the linerboard follows the flute structure of the corrugated medium, which diminishes the effective surface smoothness. As washboarding increases, the unevenness in print density increases *(9)*, with the print density on the linerboard at the flute tips differing from that in the valleys. This result is similar to the case of preprinted linerboards, in which the increasing surface roughness of the linerboards increases the unevenness of print (as discussed in the preceding section under "Surface Smoothness or Roughness").

Washboarding can be judged visually by looking at the surface of a corrugated board. On the other hand, there is no published method on how the degree of washboarding can be quantitatively evaluated. For example, Haglund reported that washboarding varies from 50 µm to 200 µm, depending on the flute type and the grammage of the linerboards *(9)*. However, no information was given about the measuring technique. It is also unclear whether or not air-leak instruments such as the Bendtsen and Sheffield testers are suitable for measuring the surface roughness of combined boards, because the surface roughness depends not only on the microroughness and macroroughness of the linerboard before corrugating, but also on the supermacroroughness related to washboarding.

Factors that affect washboarding

Washboarding is mainly caused by excessive adhesive on the shoulders of the flute tips, which pulls the linerboard down around the flute during consolidation *(2)*. Wash-boarding is affected by these factors:

- The ability of the linerboard to resist deformation
- The type and contour of the corrugated medium
- The amount of adhesive applied
- The ability of the adhesive to penetrate the medium.

The adhesive's ability to penetrate is in turn affected by the porosity and absorbency of the corrugated medium and by the viscosity of the adhesives.

The finding that washboarding decreases with increasing basis weight of the linerboard may be attributed to the liner's increased resistance to deformation *(9)*. Similarly, it is commmonly known in the corrugated industry that the B-flutes give a better printing surface than the A-flutes, since the A-flutes are higher and wider *(60)*. More detailed discussion about the bond development between the liner and the flute medium can be found in the work of DiDominicis and Klein *(2)*.

Summary

The conventional wisdom that surface roughness, porosity, and water absorbency are important for flexographic printability of linerboards has been qualitatively confirmed. However, common tests such as the Cobb water absorption test and tests for measuring air permeability bear little or no relevance to flexographic print quality. It is also unclear whether or not the Sheffield roughness tester is useful in predicting the flexo printability of linerboards.

On the other hand, the flexo print quality of linerboards appears to correlate to a certain extent with the surface roughness estimated using the Bendtsen and the PPS testers. The water absorbency determined with the IGT and the Bristow tester also appears to be helpful.

Much remains poorly quantified in the search to improve the flexo printability of linerboard. Is it more efficient to improve the print, for example, by increasing the surface smoothness with calendering or by reducing the water absorbency through sizing? As printing speeds increase and flexo inks become more viscous, factors such as pH, wettability, and surface strength may weigh more heavily in determining the flexo printability of the liners.

Even less is known about the flexo printability of combined boards. The image quality of post-printed corrugated boards depends not only on the surface properties of the liner but also on the structure of the fluted medium and the super-macroroughness of the linerboard to the extent to which it is affected by washboarding. Research has not yet established the usefulness of current laboratory testing methods in predicting the flexo printability of combined boards. TJ

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