Pre-damping effects on water absorption and drying dynamics in flexographic printing

JANET PRESTON, ELI GASKIN, AND MARTTI TOIVAKKA

ABSTRACT: Optimizing flexographic printability can involve the ink and the substrate, as well as the printing process. It has been widely reported in the literature that controlling topography of the substrate and its porosity are vital for good flexographic printability, especially when using water-based inks.

This study focuses on how pre-damping a surface impacts liquid absorption and improves wet trapping (ink on ink with no intermediate drying) in flexographic printing. A Prüfbau universal print tester was adapted to analyze flexographic wet-on-wet ink printing and trapping using yellow and magenta inks for contrast. Slow drying of the first ink layer (yellow) leads to mottle when the second layer (magenta) is applied.

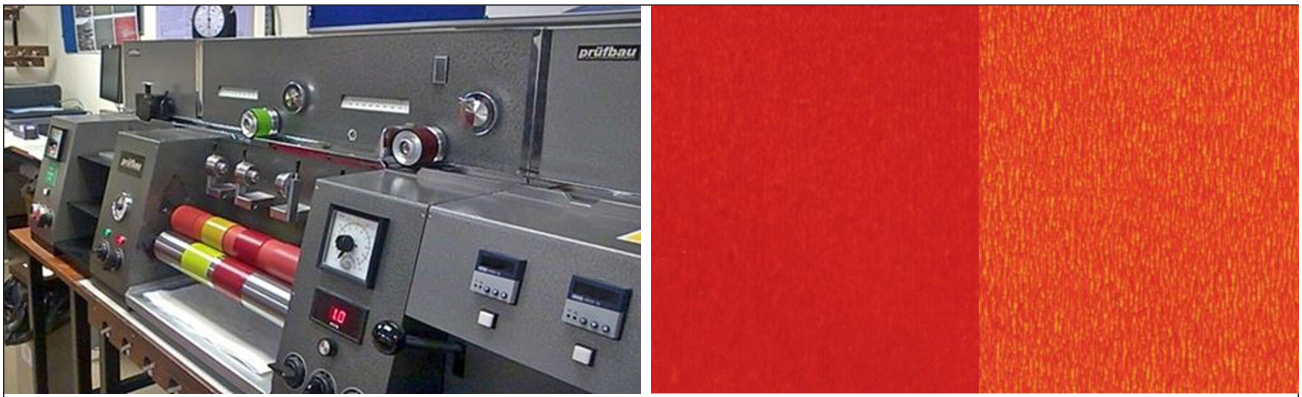
The study explores the "wet sponge" hypothesis: a pre-damped surface should absorb liquid faster. The Lucas-Washburn equation describes long-term absorption, but it does not capture short-term uptake, which instead follows a linear dependence on time.

Application: The work presented here concerns the speed of fluid imbibition into a coating layer in the context of flexographic printing. However, this is also valid for other printing techniques, such as inkjet and offset lithography, where water needs to be quickly removed from the ink. Control of coating porosity with mineral and binder choice, as well as topography and surface energy, are already well-known factors in impacting good print quality and are often discussed in the literature. The technique of moistening the surface provides another lever in the design of coating for printing.

The control of fluid absorption rate into uncoated and coated paperboards is crucial for optimal printing performance. Understanding the roles of porosity, pore structure connectivity, surface topography, evenness, and surface energy in fluid absorption is essential [1,2]. In printing processes, such as water-based inkjet and flexographic printing, absorbing significant fluid solvent volumes while fixing the color at the surface is a key requirement. However, wet trapping of water-based flexographic ink on coated boards can be problematic, especially when drying capabilities are limited [3,4]. Multicolor printing can result in slow drying of the first ink layer and reticulation or rejection of the second ink layer, leading to mottle and poor print quality.

This issue is typically addressed by selecting a coating formulation with the right combination of pigments and binders. Gane and Ridgway [5] studied flexographic printability and showed that the absorption of the fluid phase of a water-based flexographic ink was affected by the formation of a filter cake of ink pigment on the coating surface and the distribution of the dissolved polymer between the filter cake and the coating layer. The system could be optimized by adjusting the surface area to the porosity ratio of the paper coating surface. They followed up on this work by studying pressed tablets made with an ultrafine silica or a modified calcium carbonate that has a spherical porous structure covered in small platy crystals. Using the polymer containing fluid phase from a flexographic ink and pore core modeling software, they were able to predict and show faster absorption with a broad pore size distribution compared to both small or large mono-sized pores [6]. Koivula et al. [7] also saw a similar phenomenon when looking at offset printing and pre-damping with fountain solution. The importance of the polymer content in the ink on its rheology and print properties was also discussed by Olsson et al. [8].

Salminen [9] investigated the short-time uptake of water into uncoated paper and demonstrated that, in the initial regime, the liquid penetration proceeds linearly with time. This behavior contrasts with the classical Lucas-Washburn equation, which predicts a square-root dependence on time. In 2005, Gane [10] suggested that the whole pore size distribution should be used rather than a typical pore size and that fluid is absorbed via preferred pathways through fine connected pores with intermediate pore reservoirs. He used the Bosanquet equation [11] to take into account inertia at very short wetting times. Ström et al. [12] studied absorption of small sessile droplets into paper and reported that the initial absorption rate scaled linearly with time, a behavior they also attributed to an inertial flow regime. In 2014, Songok et al. [13] reanalyzed Salminen's data and showed that, at short times, the absorption rate is slowed



(a) *(b)*

1. (a) Laboratory Prüfbau printer, with printer conditions as follows: speed, 1/ms; pressure, 300 N; 1 mL yellow and 0.5 mL magenta diluted ink applied to distribution rollers; timing, 10 s inking and spreading; movement, linerboard moves left to right.
(b) Examples of good and poor ink trapping: left image, good wet trapping, with little show through of yellow from layer underneath; right image, poor wet trapping, with yellow ink seen as yellow spots.

down and governed by the dynamic contact angle, which in turn is controlled by molecular processes occurring in the gas phase ahead of the advancing liquid front. The linearized molecular kinetic theory model introduced by Blake [14] was found to accurately describe this regime, including the observed acceleration of absorption with increasing temperature, which could not be explained by inertial effects or the temperature dependence of viscosity.

In the current work, we explore the impact of pre-damping the surface prior to printing to determine if this can help speed up liquid absorption and improve flexographic wet trapping. The hypothesis is similar to the use of a pre-damped sponge; a dry sponge will not pick up much moisture, but a pre-damped one will pick up a significantly higher volume of fluid!

METHODS

The challenge of printing two-colored flexographic inks "wet-on-wet" onto a substrate without having to stop and clean the press was quite considerable due to the fast drying of the ink layer. We adapted the Prüfbau universal printability tester (Prüfbau; Peissenberg, German), typically used for offset printing, to develop a new test method. This modified approach allowed us to use the instrument to study flexographic ink trapping, specifically, wet-on-wet ink printing and trapping. The method offers the flexibility to apply a second ink layer either immediately after the first or following a predetermined delay. For our analysis, we selected yellow for the first ink layer and magenta for the second, as this combination provided adequate contrast for wet trapping analysis.

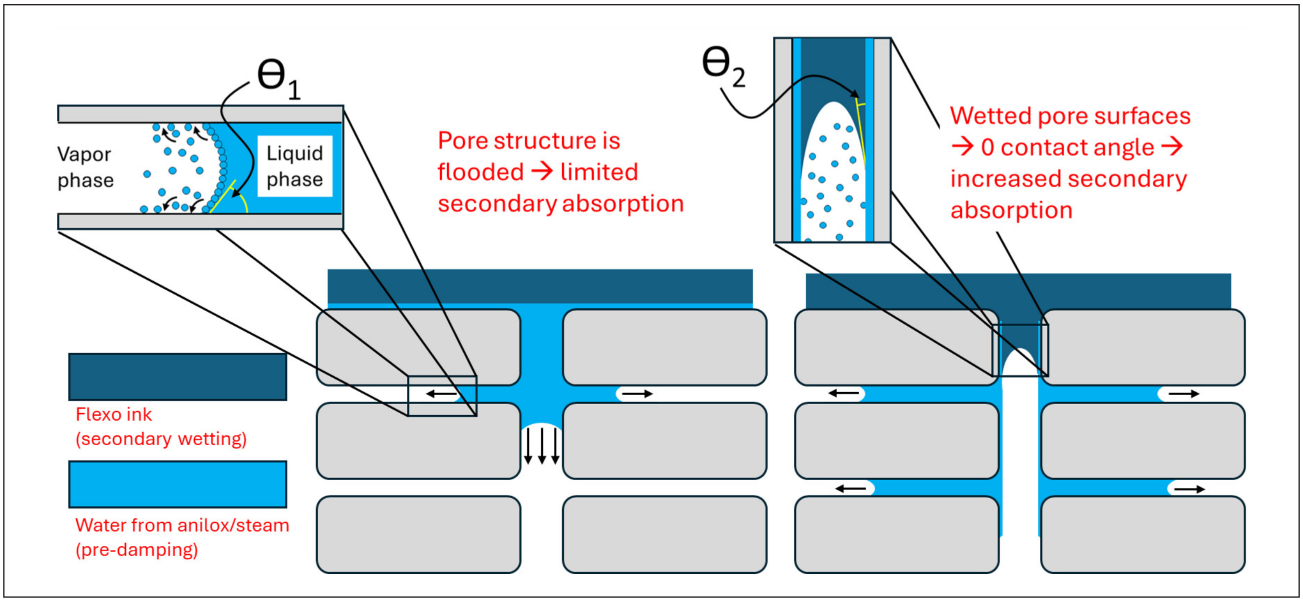
If the first layer of yellow ink dries too slowly, mottle occurs when the subsequent magenta ink is printed onto the surface, which can be seen as a "show-through" of yellow spots, as shown in **Fig. 1**. The amount of yellow showing through the magenta can be quantified by splitting the printed color image into CMYK channels and identifying areas where there is a lack of magenta. The area of each yellow show-through spot is measured and relates to the ink drying speed. The mean average grey level of the scanned image relates to the color of the image (higher value = more yellow), and the standard deviation indicates more variation, i.e., mottle. To understand the influence of pre-damping the paper surface, a Prüfbau pre-damping roller was used to apply a set amount of fluid (water). The two-color printing was either carried out immediately after, or with a set delay between, water application and printing.

MATERIALS

The boards were sourced from a paper mill that was able to supply a precoated board and the same board with a topcoat, calendered, and uncalendered as follows:

1. Precoated white top linerboard (no topcoat): Mill coated using a blade coater, calcium carbonate precoat (60% < 2 µm, with 12 pph latex; 0.45 polyvinyl alcohol [PVOH]; and a target coat weight of 15 g/m²).
2. Double-coated linerboard (uncalendered): topcoat application 85 pph narrow particle size distribution calcium carbonate and 15 pph kaolin; 14 pph latex; 0.3 pph PVOH; coat weight 11 g/m².
3. Double coated linerboard (calendered): calendered under standard laboratory condition of 100°C and 80 kN/m pressure; two nips.

The magenta and yellow flexographic inks were commercially available SolarAqua inks from Sun Chemical (Parsippany, NJ, USA). The inks were diluted from stock to a viscosity of 30 s Ford B4 cup magenta and 1 min 45 s Ford B4 cup yellow. Then, 1 mL of yellow and 0.5 mL of magenta of the diluted inks were applied directly to the Prüfbau rollers for distribution before passing to the printing plate.



2. Hypothesis for the influence of pre-damping on subsequent absorption, where θ_2 angle is less than θ_1 due to pre-damped pore surfaces.

RESULTS

This study investigates the effect of pre-damping on the absorption of flexographic inks into coated linerboard. Typically, in the absence of external pressure-driven flow, the Lucas-Washburn (LW) equation [15,16], is used to describe liquid penetration into porous materials like paper. The premise of the LW is that capillary forces at the advancing liquid front are counterbalanced by hydrodynamic drag of the liquid being pulled into a capillary. Although this simplified model seems to explain long-term absorption phenomena where the liquid front has deeply penetrated the paper surface, it has been found insufficient to explain short-term absorption phenomena.

Salminen's [9] experiments demonstrated that short-term water absorption into paper follows a linear relationship with time, rather than the square root of time as predicted by LW. Songok et al. [13], in their analysis of Salminen's data, highlighted the role of the dynamic contact angle, governed by wetting-line friction and molecular adsorption processes occurring ahead of the advancing front. In practice, this implies that pre-damping the surfaces of a porous material, such as paper, should lower the dynamic contact angle and speed up the subsequent absorption of applied liquid, as illustrated in **Fig. 2**. This hypothesis was confirmed for uncoated papers by Koppolu [17], who examined sequential water absorption into uncoated linerboard. The current work explores the same mechanism for pigment coated paperboard.

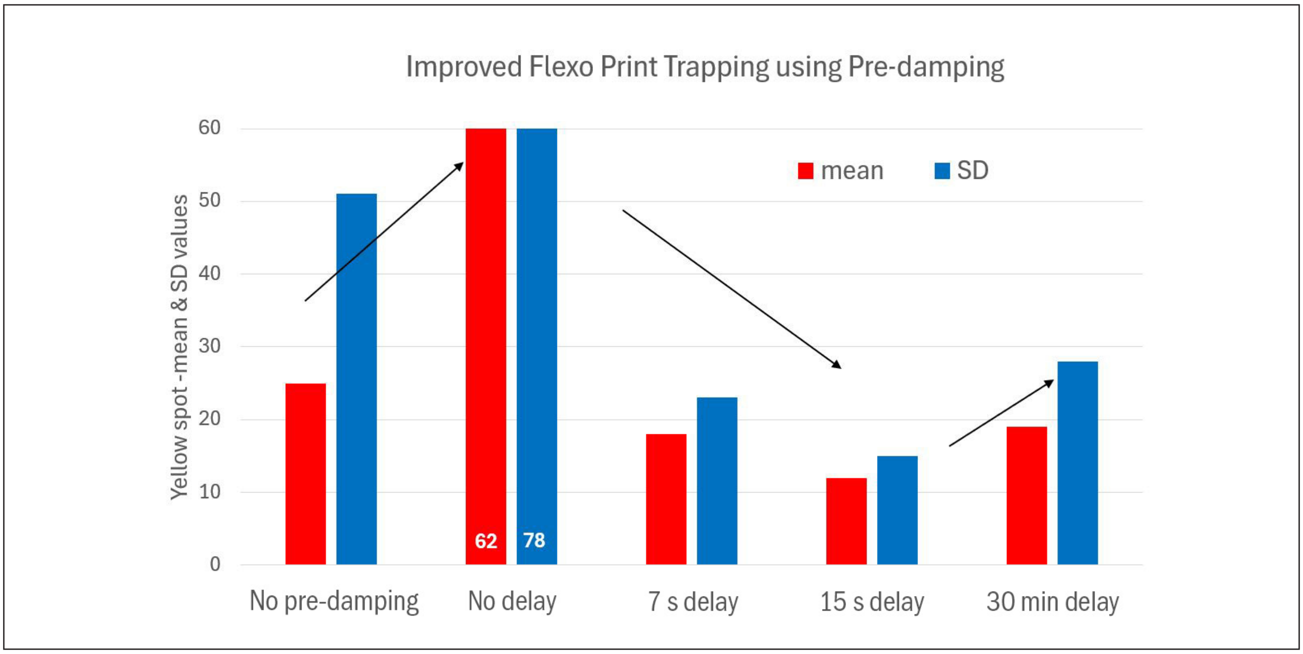
The results show that pre-damping the paper, either by applying a thin layer of water with an anilox or by using steam treatment, does improve the wet ink trapping. There seems to be an optimal amount of water that can be applied: too much water floods the surface, preventing further absorption, while too little water has minimal or no impact.

Figure 3 shows results for trapping without and with pre-damping for a double-coated linerboard. When the time delay between the pre-damping and subsequent printing was varied from no delay up to 30 min, significant differences in the trapping can be seen. The standard trapping, with no water added to the surface, was quite poor. With no delay between pre-damping and printing, the trapping became significantly worse, as the water did not have time to exit from the pores before the ink application, as schematically shown on the left side of Fig. 2. However, when there were longer delays of 7 s or 15 s prior to printing, the wet trapping improved considerably. With the extremely long delay of 30 min, the surface had partially dried and the trapping mottle increased.

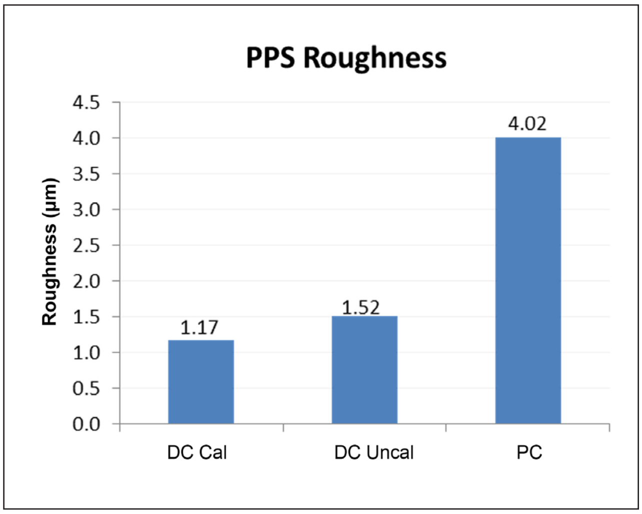
Impact of board roughness

Roughness is a known issue for flexographic printing. If there is no contact between the plate and the substrate, then this can lead to lack of ink transfer. Alternatively, a relatively high pressure on the roughness peaks can cause the fluid ink to be pushed to the sides. The topic of uncovered areas in flexographic printing has been discussed by Bohlin [18], who linked it to both local roughness variations and to local wettability variations on the surface.

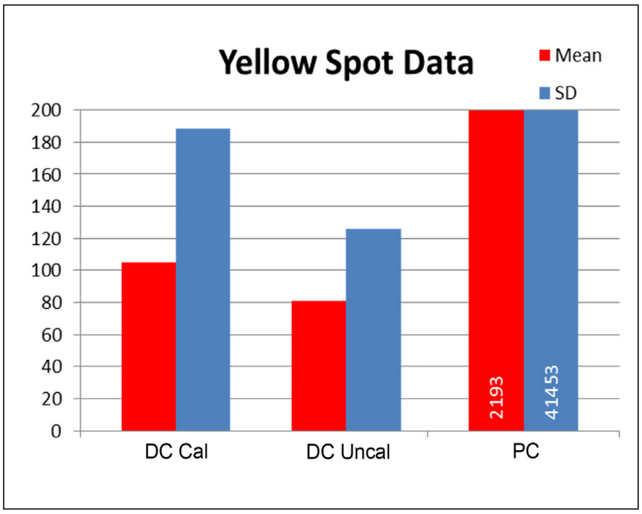
For this reason, boards with three different roughness levels were assessed: a precoated only surface, a double-coated surface uncalendered, and the same double-coated board after calendering. The PPS roughness values are given in **Fig. 4** and show that the precoated ("PC") was ~4 times rougher than the double coatings. In **Fig. 5**, the trapping results are shown, and the rough precoat had a very



3. Trapping becomes poorer after application of pre-damping water, with no delay before printing. When a delay is made between damping and printing, the trapping improves (SD: standard deviation).



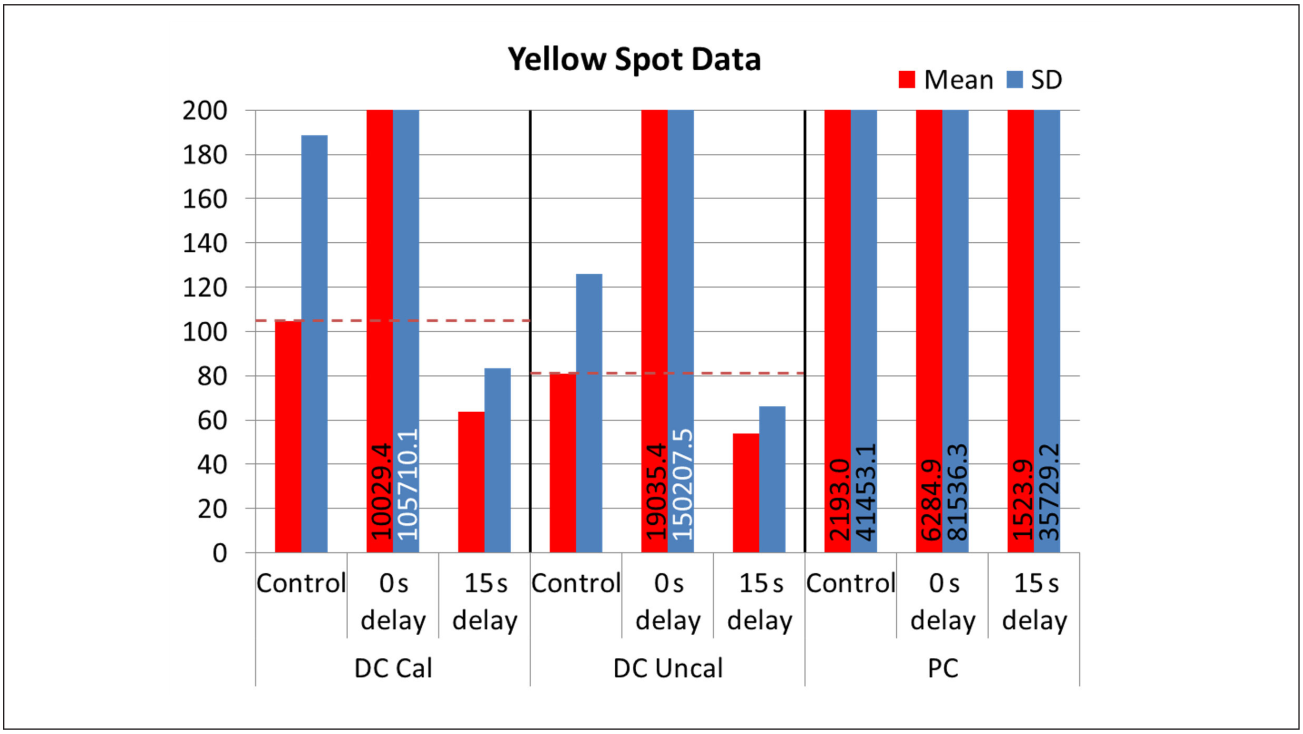
4. Parker Print Surf (PPS) roughness of coated boards 1000 kPa, µm (DC Cal: double-coated calendered; DC Uncal: double-coated uncalendered; PC: precoated).



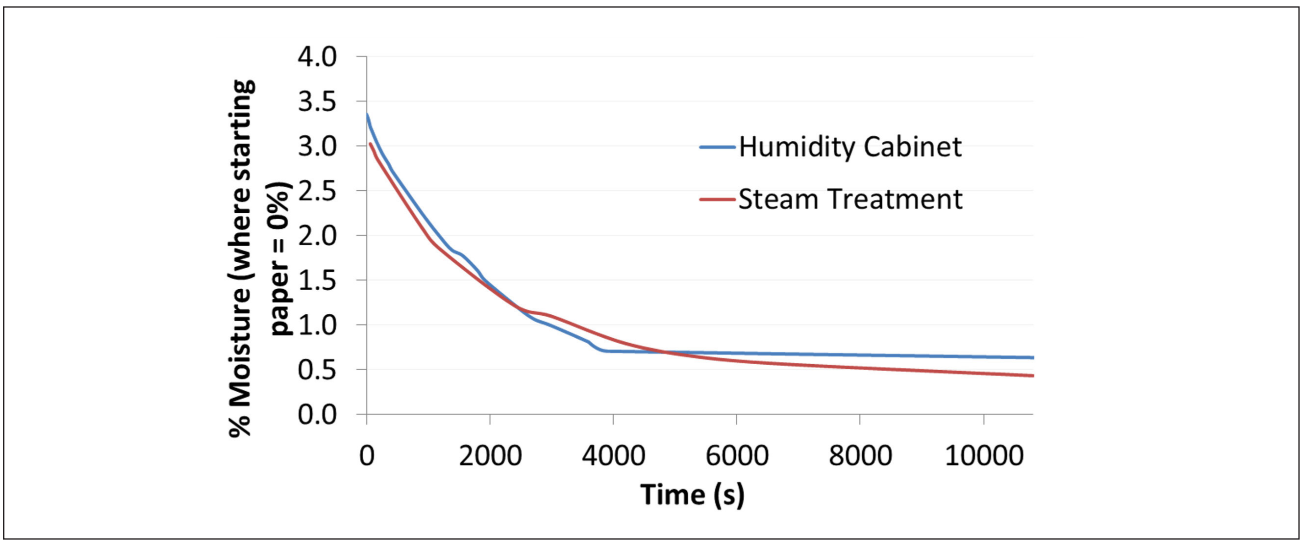
5. Yellow spot trapping results showing the best performer to be the double-coated but uncalendered sample (DC Cal: double-coated calendered; DC Uncal: double-coated uncalendered; PC: precoated).

high unevenness/mottle. The double-coated calendered ("DC cal") was smoother than the uncalendered ("DC uncal"); however, the flexographic trapping was better for the uncalendered. We believe the calendering had caused compression of the pores, leading to a lower porosity and slower drying of yellow ink, showing itself as less effective in flexographic trapping (higher yellow spot), which resulted in a higher yellow spot value.

The results for pre-damping of the coatings are shown in **Fig. 6**. Once again, we see that the very rough precoat-only board shows significant mottling of the ink, which we see as a high yellow spot number. We still see a higher degree of mottle with no delay between wetting and pre-damping and an improvement after waiting for 15 s before printing. However, the overall roughness obscures the visual result. The double-coated uncalendered samples are significantly smoother and have a lower intrinsic starting mottle. When pre-damped with no delay, the mottle becomes significantly worse, as the surface is flooded. Waiting for 15 s before printing gives the lowest degree of mottle and the best wet-on-wet ink trapping. The same pattern is also observed when the double-coated board is calendered. However, in this instance the trapping is slight-



6. Trapping results for the three board samples with pre-damping and immediate printing, and also pre-damping and a delay of 15 s before printing (SD: standard deviation; DC Cal: double-coated calendered; DC Uncal: double-coated uncalendered; PC: precoated).



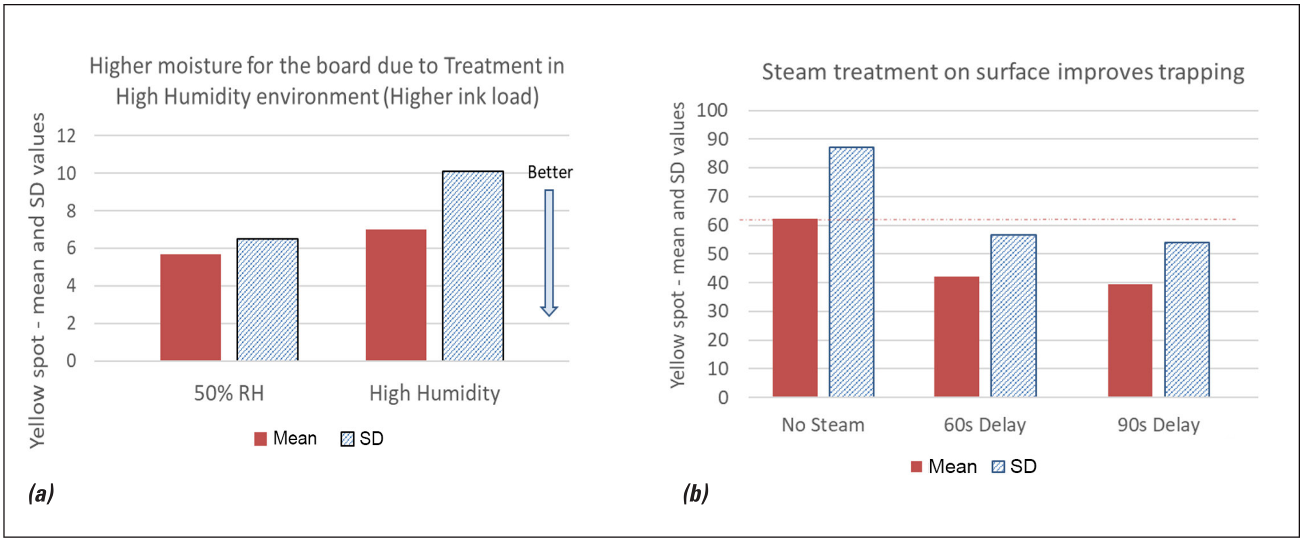
7. Moisture uptake and subsequent loss after moisturizing; storage in a conditioned laboratory.

ly worse. This may be due to some compression of the board during the calendering process, which results in slightly slower ink solvent removal.

Application of moisture

Two additional ways of applying moisture to the coated linerboard prior to the flexographic printing were investigated: (1) by changing the moisture content of the whole board via storage at high humidity overnight, and (2) by steam application to the coating surface.

Samples of the coated linerboard were treated with either high humidity or steam prior to being flexographic printed. Assessment of the amount of water transferred to the paper and lost with time was made by weighing under controlled conditions. The two different methods of moisturizing the paper transferred similar amounts of moisture to the board (~3%–3.2% after 24 h) and followed very similar moisture loss with time in a controlled atmosphere laboratory (50% RH, 23°C) after being removed from the moisturizing system (**Fig. 7**).



8. (a) Effect of high relative humidity (RH) and (b) steam treatment on flexographic ink trapping in linerboard (SD: standard deviation).

Figure 8a shows that the high humidity sample gave slightly worse trapping than the control sample, possibly due to roughening caused by fiber swelling. Bulk moisturizing of the sample appears to have no positive impact for flexographic ink trapping.

However, application of steam to the paper surface proved to be a useful way for introducing low levels of moisture in order to improve ink trapping, as shown in Fig. 8b. The steam was directed at the surface of the coating for only a few seconds.

SUMMARY OF KEY FINDINGS

Below are observations based on the current study:

- Pre-damping with water or steam can improve wet ink trapping, but there is an optimal amount of water; too much floods the surface, too little has no effect.
- A delay between pre-damping and printing improves trapping; immediate printing after pre-damping worsens it due to flooding of the surface pores.
- Surface roughness significantly affects print quality. Smoother surfaces are generally better, but calendering, which compresses pores, can slightly worsen ink trapping. This is probably due to the reduction in pore volume near the sheet surface.
- Steam application to the surface improved ink trapping, while bulk moisturizing of the board via high humidity storage did not. The moisture needs to be in the correct location.
- Optimizing coating porosity and topography is crucial for printability. However, a second way of controlling ink solvent imbibition includes pre-damping with an optimal amount of water, which then largely leaves the surface but wets the pore surfaces, thereby lowering the dynamic contact angle to speed up subsequent ink absorption.

CONCLUSIONS

Controlling the coating porosity and topography of a coated paper or board is vital to ensure optimum printability performance. This has been studied quite extensively. The literature reports the importance of a smooth and even coating or board surface and sufficiently high pore volume made up of a broad distribution of pore sizes.

In this study, we looked at a different aspect of the coating, which was the impact of pre-damping on subsequent absorption of ink solvent. This was particularly to solve the issue of poor wet-on-wet flexographic ink trapping.

Surface application of water affects the flexographic printability of coated linerboard. However, excessive water can fill the surface pores, resulting in low wet ink trapping and poor print quality. With an optimal amount of water, most of it will leave the paper surface, still wetting the pore surfaces and thereby enhancing printability. This improvement is due to the lowered dynamic contact angle, which speeds up the subsequent absorption of flexographic ink. In practice, the phenomenon is similar to the “wet sponge” principle, where a damp sponge absorbs water more readily than a dry one.

When printing two colors, surface roughness has a greater impact than surface porosity and water absorption. A smooth surface is preferable to a rough one; however, if calendering closes the surface pores, ink trapping can slightly worsen.

Pre-damping by surface application of steam enhances ink drying and flexographic trapping. However, using similar moisture levels by conditioning in high humidity does not yield the same benefits, highlighting the importance of moisture distribution within the paper structure. **TJ**

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ABOUT THE AUTHORS

This study was initiated because of issues in flexographic printing with wet-on-wet ink trapping experienced by some coated board producers. There was considerable difficulty in reproducing the issue in the lab, which made it difficult to solve, so a lab test was therefore developed. Using this, we looked at different aspects of the coating structure to impact flexo printing, and then, as an extension, we studied the impact of pre-damping.

This particular study focused on the impact of pre-damping with moisture on flexographic wet trapping. Previous work has looked at the physical coating structure achieved by blending pigments in order to maximize porosity and speed up ink drying. Both aspects, together with binder level, are important for flexo ink drying and wet trapping.

The most difficult part of the work was the initial development of the flexo trapping test. Using the standard flexo laboratory printer, it was not possible to print two colors on top of each other fast enough to see the issue. Utilization of the Prüfbau multipurpose printer, which is generally used for offset printing, was the biggest challenge and biggest achievement!

Creating a new test that reproduces a real-life issue and using this test to solve problems was particularly rewarding. It was also interesting to see the scientific reasoning and also a real-life application for the "wet sponge effect" that we all know, where a damp sponge picks up fluid far more effectively than a bone dry one.

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Toivakka

Using the information here, paper and board mills will have one more tool with which to improve or control flexographic printing. Our next step is to use the different aspects of coating structure and moisture to optimize coatings in order to achieve excellent flexographic printing as needed. It would also be interesting to determine if this pre-damping could also speed up the drying of water-based inkjet inks. This could be important for inkjet variable data marking of packaging (sell by dates and QR codes), as well as full color inkjet printing.

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