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Investigation of the Influence of Opaque White Ink Addition on Colour Characteristics of Some Process and Pantone Colours Printed with Water-Based Flexo Inks on Kraft Papers

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ABSTRACT

One of the major challenges in flexographic printing on kraft papers is the accurate reproduction of colour, which is strongly affected by the inherent yellow-brown shade of the printing substrate. Due to the limited opacity of most process and spot-colour inks, including CMYK and Pantone water-based flexographic inks, significant deviations in colour appearance occur when they are printed directly on kraft-based materials. The conventional technological solution is the application of one or more opaque white ink underlayers in order to create a sufficiently white printing base. However, this approach is associated with several disadvantages, including increased production costs, additional printing units or passes, the need for extra flexographic printing plates, higher ink consumption, and possible technical problems such as anilox roller clogging caused by the highly pigmented nature of opaque white inks. The present study investigates an alternative approach based on the addition of different quantities of opaque white ink directly into water-based flexographic process inks and Pantone inks. The influence of this modification on the colour characteristics and colour reproduction accuracy was evaluated by measuring the spectral properties and opacity of the white ink, as well as the CIE Lab colour coordinates of the printed samples. Colour differences, expressed as ΔE values, were determined in relation to reference colour characteristics. The inks were printed on brown kraft liner and on white double-coated testliner. Comparative analyses were performed between inks printed on a white substrate and inks printed directly on kraft material with the addition of varying amounts of opaque white ink. The results demonstrate a significant improvement in the colour accuracy characteristics of inks printed on brown kraft paper when opaque white ink is added to the ink formulation. Depending on the investigated ink colour, the colour difference from the reference values was reduced by approximately 30–40%. These findings indicate that controlled addition of opaque white ink may represent an effective technological approach for improving colour reproduction accuracy in flexographic printing on kraft-based substrates. The results are of both scientific and practical importance and are particularly relevant to high-volume printing of corrugated board and packaging production, where kraft papers are widely used and colour consistency remains a critical quality requirement.*

KEY WORDS

Packaging, flexography, water-based flexography inks, opaque white ink, kraft papers, colour reproduction accuracy, colour difference, corrugated board

1. Introduction

Flexographic printing is widely used in packaging production, particularly for corrugated packaging, due to its sustainability for a board range of substrates and high-volume manufacturing. Kraft-based papers are commonly used in this field, however, their inherent brownish colour, resulting from the fibre characteristics and manufacturing process can significantly affect the colour appearance of printed images. Water-based flexographic inks are widely applied in packaging production, but the relatively low opacity of most process and spot-colour inks allows the substrate to contribute substantially to the final optical response. This becomes particularly important when standardized or reference colours must be reproduced accurately.

The colour characteristics of a printed surface depend not only on the optical properties of the ink but also on the substrate. When the ink layer has limited opacity, the colour and reflectance of the substrate influence the amount and spectral distribution of reflected light, resulting in measurable changes in the colorimetric characteristics of the printed image.

Brown kraft liner provides a significantly different optical background compared with the white substrates commonly used for characterizing process and spot colours. In addition, light scattering within the paper structure and ink penetration into the substrate influence the relationship between the physical ink layer and its measured optical response. These effects can be quantified using the CIE L*a*b* colour space, while the deviation from a reference colour can be expressed as a colour difference (ΔE), providing a quantitative measure of colour reproduction accuracy.

A conventional technological solution for reducing the influence of the coloured substrate is the application of an opaque white ink underlayer beneath the process or spot-colour ink. Due to its high pigment concentration and opacity, the white layer provides a lighter and more neutral optical background and reduces the contribution of the kraft substrate to the reflected light. However, the use of a separate white underlayer introduces additional technological and economic requirements, including an additional printing unit or pass, an extra flexographic printing plate, increased ink consumption, and additional requirements for ink handling, equipment cleaning, and anilox roller maintenance. These limitations are particularly relevant in high-volume packaging production, where production efficiency, material consumption, and process stability directly affect manufacturing costs.

An alternative approach involves the controlled addition of opaque white ink directly to the coloured ink formulation, thereby reducing the influence of the kraft substrate without requiring a separate white underlayer.

To the authors' knowledge, the application of this approach to Pantone inks printed on kraft substrates, under the conditions investigated in the present study, has not previously been reported. Therefore, the present work represents an innovative experimental investigation aimed at establishing the potential of this method for modifying the colour characteristics of Pantone inks and improving their colour reproduction accuracy on kraft substrates. Different quantities of opaque white ink are incorporated into the Pantone ink formulations, and their effects on the resulting colour characteristics and reproduction accuracy are experimentally evaluated.

The aim of the present study is therefore to investigate the influence of controlled additions of opaque white ink to water-based flexographic process and Pantone inks when printed on kraft-based substrates. The experimental analysis compares the colorimetric characteristics of inks printed on a white double-coated testliner with those obtained when the same inks are printed directly on brown kraft liner with varying amounts of opaque white ink added to the formulation. The influence of the white ink addition is evaluated using spectral characteristics, CIE L*a*b* and LCh° colour coordinates, and colour differences (ΔE) relative to the corresponding reference characteristics. Particular attention is given to the extent to which the addition of opaque white ink modifies the lightness, chroma, and hue of the printed inks, reduces colour deviation, and improves reproduction accuracy. This approach enables a more comprehensive assessment of the colourimetric response of the ink formulations and their potential as a technically viable alternative to a separate opaque white underlayer in flexographic packaging production.

2. Materials and methods

2.1. Printing substrates

Two paper substrates were used in the experimental investigation: brown kraft liner and white double-coated testliner. The selected substrates represent two different optical backgrounds for evaluating the influence of opaque white ink addition on the colour characteristics of water-based flexographic inks.

The brown kraft liner was selected as the primary substrate for the investigation because its characteristic brown coloration provides a strongly coloured background that can influence the colorimetric characteristics of inks printed directly on its surface. The substrate's physical properties were experimentally measured, resulting in a grammage 140 g/m² and a thickness of 160 µm. Its relevant optical characteristics, including brightness, were likewise experimentally determined rather than sourced from manufacturer specification.

A white double-coated testliner with an experimentally measured grammage of 140 g/m² and a thickness of 140 µm was used as the reference substrate. Its bright, coated surface provides a substantially different optical background compared with the brown kraft liner and allows the colour characteristics of the investigated inks to be evaluated under reference-like printing conditions.

Prior to printing, the substrates were conditioned under controlled laboratory conditions of 25 °C and 40 % relative humidity for 24 hours. The samples were stored and handled under the same conditions throughout the experimental procedure in order to minimize the influence of environmental conditions on the measured colour characteristics.

The main characteristics of the printing substrates are summarized in Table 1.

2.2. Printing inks

Water-based flexographic inks from the NAB pigment concentrates series supplied by Druckfarben Group, were used in the experimental investigation. The ink set comprised one process colours – cyan, and one Pantone spot colour – Pantone 300. All investigated inks were formulated for flexographic printing and were used as supplied, except for the controlled addition of opaque white ink described in Section 2.3.

The process ink was selected to represent the principal chromatic components of process-colour printing, while Pantone 300 was selected as representative spot colours with different chromatic characteristics. The inclusion of both process and Pantone inks enabled the influence of opaque white ink addition to be evaluated across different ink formulations and colour characteristics.

Table 1

Characteristics of the printing substrates

Substrate	Grammage [g/m²]	Thickness [µm]	Brightness (ISO R457)	Colour characteristics		
				L*	a*	b*
Brown kraft liner	140	160	0.12	57.54	11.13	26.65
White double-coated testliner	140	140	0.96	93.04	0.50	-2.92

The main physical and optical characteristics of the investigated inks, as provided by the manufacturer and/or determined experimentally, are summarized in Table 2. The measured or specified parameters include viscosity, optical density and CIE Lab colour coordinates. During the experimental procedure, optical density parameters were determined spectrophotometrically. Cyan ink measurements were performed in accordance with ISO 12647-6 and ISO 5-4 (Status T density) (International Organization for Standardization, 2020), whereas Pantone 300 was evaluated at its maximum absorption wavelength, with the dominant spectral density wavelength determined as λ=610.

Particular attention was given to the optical characteristics of the inks because their opacity and interaction with the substrate are directly relevant to the colour reproduction of prints produced on brown kraft liner. The reference colour characteristics of the investigated inks were determined from prints produced on the white double-coated testliner.

These reference samples were subsequently used for comparison with prints produced on the brown kraft liner with different amounts of opaque white ink incorporated into the respective ink formulations.

2.3. Opaque white ink

An opaque white water-based flexographic ink from the NAB pigment concentrates series supplied by Druckfarben was used as the white component in the experimental formulations.

The ink was selected based on its high opacity and hiding power, which are essential for reducing the optical influence of the brown kraft substrate on the colour characteristics of subsequently printed inks. The relevant physical and optical characteristics of the opaque white ink were obtained from the manufacturer's technical documentation and, where necessary, determined experimentally. The investigated parameters included viscosity and density.

Table 2

Characteristics of the investigated water-based flexographic inks

Ink	Ink type	Viscosity ISO 2431 [sec]	Optical density	Colour characteristics		
				L*	a*	b*
Cyan	Process	20	1.35	50.00	-37.00	-50.00
Pantone 300	Spot colour	20	1.56 ($D_{\lambda 610nm}$)	36.45	-8.15	-64.07

Particular attention was given to the optical properties of the white ink, including its spectral characteristics and opacity, as these properties determine its ability to mask the underlying substrate and modify the optical response of the resulting ink layer.

The spectral characteristics of the opaque white ink were determined by spectrophotometric measurements, using X-Rite eXact 2 device. The obtained characteristics were subsequently used to assess the suitability of the white ink for incorporation into the investigated process and Pantone ink formulations.

The investigated ink formulations are summarized in Table 3.

Table 3
Experimental ink formulations

Parameter	Value	Method / Source
Product / Ink series	NAB pigment concentrates	Manufacturer
Colour	White	Manufacturer
Ink type	Water-based flexographic	Manufacturer
Viscosity [sec]	20 (DIN4 cup)	ISO 2431 (International Organization for Standardization, 2019)
Density [g/cm^3]	0.98 – 2.09	ISO 2811-1 (International Organization for Standardization, 2016)

2.4. Ink formulation and white ink addition

To investigate the influence of opaque white ink addition on the colour characteristics of the selected water-based flexographic inks, controlled amounts of opaque white ink were incorporated directly into the original cyan and Pantone 300 ink formulations. For each investigated colour, the original ink without added white ink was used as the control formulation. The opaque white ink was added in predefined proportions of 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50%, respectively. The selected addition levels were identical for all investigated ink colours and were chosen to evaluate the effect of progressively increasing white ink content on the colour characteristics of the resulting formulations. The required amounts of coloured and opaque white inks were accurately weighed to 0.001 g and homogenized for 1 min under controlled laboratory conditions to ensure uniform formulation.

The percentage of opaque white ink addition was calculated based on the ratio between the volume of the added white ink and the initial volume of the coloured ink. Accordingly, an addition level of 5% corresponds to adding extra volume in specific grams of liquid to the initial volume. The formulation procedure and calculation method were kept consistent throughout the experiment to ensure comparability between the different ink colours and white ink concentrations.

A total of 22 modified formulations were prepared in addition to the five unmodified control formulations. The formulations were identified according to the original ink colour and the amount of added opaque white ink. The complete experimental matrix is presented in Table 4.

Table 4
Experimental ink formulations and opaque white ink addition levels

Ink	Ink type	White ink addition [w/w %]	Sample designation
Cyan	Process	0	C-0
Cyan	Process	5	C-5
...	...	...	...
Cyan	Process	45	C-45
Cyan	Process	50	C-50
Pantone 300	Spot colour	0	P300-0
Pantone 300	Spot colour	5	P300-5
...	...	...	...
Pantone 300	Spot colour	45	P300-45
Pantone 300	Spot colour	50	P300-50

2.5. Laboratory printing conditions

The prepared ink formulations were applied to the selected substrates under laboratory conditions using a K Hand Coater (RK PrintCoat Instruments Ltd., UK), a manual wire-wound bar coating system designed for the application of printing inks and other liquid coatings onto various substrates.

For the present investigation, K Bar No. 0 which white handle was used. According to the manufacturer's specifications, this bar has a wire diameter of 0.05 mm and provides a nominal wet film deposit of approximately 4 µm. The same bar was used for all investigated ink formulations in order to maintain a constant nominal ink application thickness throughout the experimental procedure.

Prior to printing, the ink formulations were thoroughly homogenized. A sufficient amount of ink was applied to the starting area of the substrate, after which the K Bar was drawn manually across the substrate in a single continuous movement to form a uniform ink layer. The same application procedure was used for all investigated formulations and substrates.

The unmodified process and Pantone ink were applied both to the white double-coated testliner and to the brown kraft liner. The modified formulations containing different amounts of opaque white ink were applied directly to the brown kraft liner. This experimental arrangement enabled comparison of the colour characteristics of the unmodified inks on the white reference substrate with those of the same ink printed directly on the brown kraft substrate, as well as with the modified formulations containing opaque white ink.

After application, the samples were allowed to dry naturally at room temperature under laboratory conditions. No additional forced drying or thermal treatment was applied. The samples were subsequently stored under the same laboratory conditions until colorimetric measurements were performed. The drying and handling conditions were kept consistent for all samples to minimize variations associated with sample preparation.

2.6. Colour measurement and evaluation

The colorimetric characteristics of the printed samples were evaluated using an eXact 2 portable spectrophotometer (X-Rite, USA). The instrument employs a 45° circumferential ring illumination and 0° viewing geometry (45°:0°).

The measurements were performed using D50 illumination, a 2° standard observer, DIN density standard, and M1 measurement condition (D50-based). The white-base setting was defined as absolute (Abs).

For the investigated cyan and Pantone 300 inks, colour differences were evaluated relative to predefined reference colour coordinates. Target CIELab* reference values for Cyan and Pantone 300 were defined in accordance with ISO 12647-6 (International Organization for Standardization, 2020) and directly from PantoneLIVE, respectively. These reference values served as absolute colorimetric baselines to quantitatively evaluation of colour reproduction accuracy of the printed samples, independently of substrate influence.

Colour differences between the measured samples and the corresponding reference values were calculated using the CIEDE2000 colour-difference formula (ΔE00), in accordance with ISO/CIE 11664-6:2022 (International Organization for Standardization, 2022). For each investigated formulation, the measured L*, a*, and b* values were compared with the corresponding reference values. Particular attention was given to changes in ΔE00 resulting from the addition of opaque white ink to the original ink formulation. The relative reduction in colour difference was subsequently used to evaluate the improvement in colour reproduction accuracy achieved on the brown kraft liner.

In addition to the colorimetric evaluation, the measured spectral data were used to characterize the optical response of the printed samples and to identify changes associated with the incorporation of opaque white ink into the coloured formulations. The resulting colorimetric and spectral data were used for comparative analysis of the unmodified and modified ink formulations under the standardized measurement conditions described above.

2.7. Data analysis

The collected colorimetric and spectral data were analysed to evaluate the quantitative impact of opaque white ink addition on the colour reproduction characteristics of water-based flexographic ink printed on a brown kraft substrate. The analytical framework focused on evaluating changes in lightness (L*), chromaticity coordinates (a* and b*), spectral reflectance curves and total colour differences (ΔE00).

Colour differences between the printed samples and the predefined target reflectance coordinates were quantified using the CIEDE2000 colour-difference formula (ΔE00). The total colour difference ΔE00 was calculated according to Equation 1.

$$\Delta E2000 = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)} \quad (1)$$

where ΔL', ΔC', and ΔH' represent the calculated differences in lightness, chroma and hue, respectively: S_L, S_C, and S_H are weighting functions that compensate for perceptual non-uniformities in the CIEL*a*b* colour space; R_T is the rotation term accounting for hue-chroma interaction in the blue region; and k_L, k_C and k_H are parametric factors set to unity ($k_L = k_C = k_H = 1$) under reference measurement conditions.

To evaluate the technological efficacy of direct white ink addition in migrating substrate interference, and relative percentage reduction in colour difference (ΔE_{red}) was calculated for each modified formulation using Equation 2.

$$\Delta E_{red} = \left(\frac{\Delta E_{00,unmodified} - \Delta E_{00,modified}}{\Delta E_{00,unmodified}}\right) * 100 \quad (2)$$

where $\Delta E_{00,unmodified}$ represents the colour difference of the baseline ink printed on brown kraft liner without white ink addition (0%) and $\Delta E_{00,modified}$ denotes the colour difference of the corresponding ink formulation containing a specific percentage of added opaque white ink (5-50%).

The influence of the substrate optical background was characterized by comparing the baseline colourimetric values (Lab* and LCh°) of unmodified inks printed on brown kraft liner with those obtained on the white double-coated testliner. Statistical trends and visual representations of lightness shift (ΔL*), chromatic

vector changes (Δa*, Δb*), LCh° variations, and the overall ΔE00 trajectory were mapped as a function of opaque white ink concentration to determine the optimum dosage for process and spot colours.

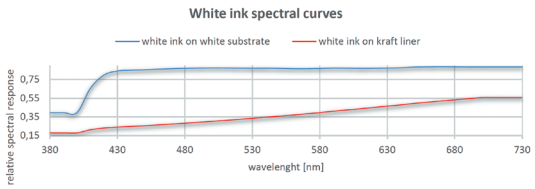
3. Results and discussion

3.1. Optical properties of the opaque white ink

The optical performance of the opaque white flexographic ink determines its capacity to mask the brown kraft substrate and modify the spectral response of the coloured ink formulations. To establish the baseline optical characteristics, the opacity, spectral reflectance and lightness parameters of the pure opaque white ink printed on the brown kraft liner and white double-coated testliner were evaluated.

The opacity of the opaque white ink was evaluated spectrally in accordance with ISO 23498:2022 (International Organization for Standardization, 2022) using the contrast ratio method, defined as the ratio of spectral reflectance measured over a standard black backing (R_b) to that over a standard white backing (R_w). The high concentration of titanium dioxide (TiO_2) pigment within the water-based flexographic vehicle provided opacity value of: 46.98% at a wet film deposit of 4 µm. This high opacity is critical for suppressing the selective light absorption of the underlying brown unbleached kraft fibres, thereby reducing the influence of substrate chromaticity on subsequently applied or blended ink layer.

The spectral reflectance curve of the pure opaque white ink across the visible spectrum (380-730 nm) is presented in Figure 1.



» **Figure 1:** *Spectral reflectance curve of pure opaque white ink*

The spectral profile demonstrates a characteristic high, uniform reflectance across the entire visible spectrum, peaking at approximately 88% reflectance in the 380-730 nm range. A slight decrease in reflectance is observed in the near-ultraviolet/violet region (400-420 nm) which is a typical for TiO2-based pigments due to fundamental band-gap light absorption in the UV spectrum.

When printed on brown kraft substrate, the unmodified white ink yielded CIEDE2000 coordinates of L*=67,56, a*=7,30, and b*=15,97. The height of L* value confirms the significant increase in surface lightness over yellowish-brown background.

These optical properties confirm that the selected opaque white ink possesses the necessary scattering efficiency to serve as an optical modifier in Cyan and Pantone 300 formulations.

3.2. Colour characteristics of process inks printed on white substrate

To establish the baseline printing performance and evaluate colour reproduction under standardized conditions, the unmodified Cyan (process) and Pantone 300 (spot) ink were printed onto the white double-coated testliner. This substrate provides a highly neutral, bright, and smooth optical background minimizing unwanted light absorption and scattering from substrate fibres.

The colorimetric values obtained on the white substrate as the reflectance standard baseline for evaluating colour deviations (ΔE00) when printing directly onto the brown kraft liner. The measures L*, a*, b* coordinates and the calculated total colour difference relative to the digital target standards are summarized in Table 5.

Table 5

Baseline colorimetric characteristics and colour differences (ΔE_{00}) of inks printed on white double-coated testliner

Ink	Ink type	L*	a*	b*	ΔE_{00}
Cyan	Process	52.26	-27.42	-54.18	4.86
Pantone 300	Spot	36.63	-7.03	-54.17	2.65

Analysis of reference prints:

- Cyan ink: Printed on the coated white substrate, the Cyan ink exhibited characteristics high lightness (L*=52.26) and strong negative b* values (b*=-54.18), indicating clear cyan chromaticity with minimal contamination from substrate undertones. The total colour difference relative to the reference standard was ΔE_{00}=4.86, confirming acceptable colour rendering under optimal optical conditions.
- Pantone 300 ink: The spot colour displayed a noticeably deeper cyan-blue tone with lower lightness (L*=36.63) and higher colour saturation compared to process Cyan. The total colour difference on the white substrate reached ΔE_{00}=2.65, establishing the benchmark colour reproduction achievable with the nominal wet film deposit (4 µm) without background interference.

These baseline values demonstrate that both inks achieve predictable colour output on a white optical background. Consequently, any colorimetric shifts observed on the brown kraft liner in subsequent tests can be directly attributed to the optical absorption characteristics of the brown substrate and the modified ink formulations.

3.3. Color characteristics of process ink printed on brown kraft liner

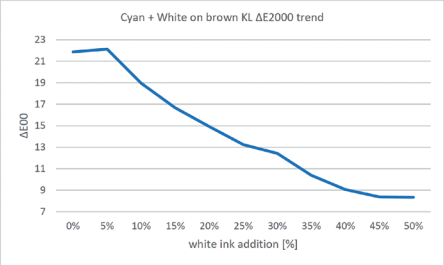
To qualify the optical degradation caused by the unbleached substrate, the baseline unmodified Cyan (C-0) and Pantone 300 (P300-0) inks were printed directly onto both the white double-coated testliner and the brown kraft liner at a constant nominal wet ink film deposit of 4 µm.

Due to selective spectral absorption of unbleached kraft fibres – which act as a strong yellow-red optical filter – the printed baseline inks exhibited a dramatic shift in colorimetric coordinates and spectral reflectance. For Cyan (C-0), reflectance in the blue-green spectral region (400-550 nm) was heavily suppressed, resulting in a lower lightness (L*) and shift toward positive a* and b* coordinates (perceived visually as a dirty, desaturated green-brown tint). Similarly, Pantone 300 (P300-0) lost its characteristic saturated cyan-blue appearance, shifting to a darker slate hue. The total colour difference (ΔE00) relative to the digital target standards reached value exceeding 12.0 for Cyan and 11 for Pantone 300, far above the acceptable industrial packaging tolerance ($\Delta E_{00} \leq 2.0$-3.0).

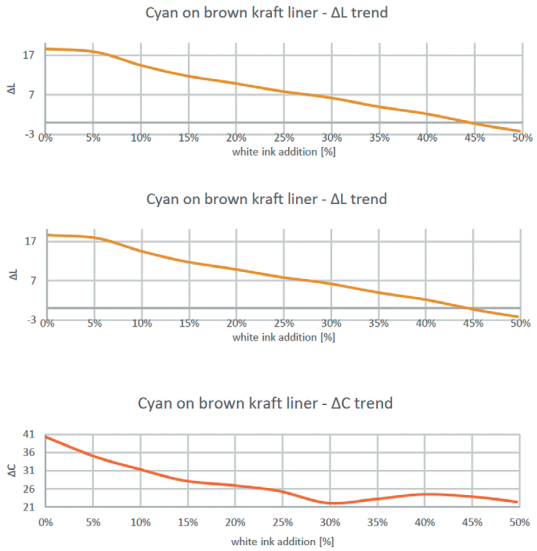
3.4. Influence of opaque white ink addition on process colours

Table 6

Physical parameters and colorimetric values of modified Cyan ink formulations printed on brown kraft liner with 0% to 50% opaque white ink additions – rheological, physical, and colorimetric characteristics

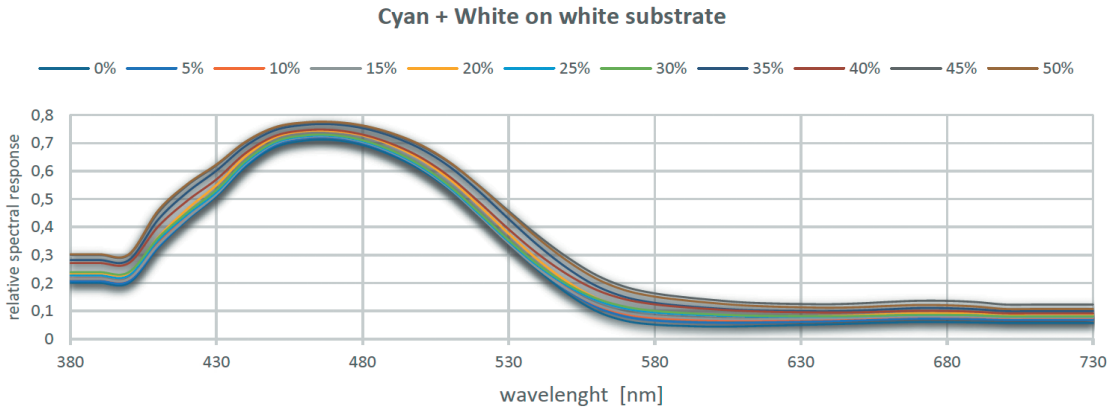


» **Figure 2:** *Colour difference of Cyan formulations as function of opaque white ink addition when printed on the brown kraft liner*

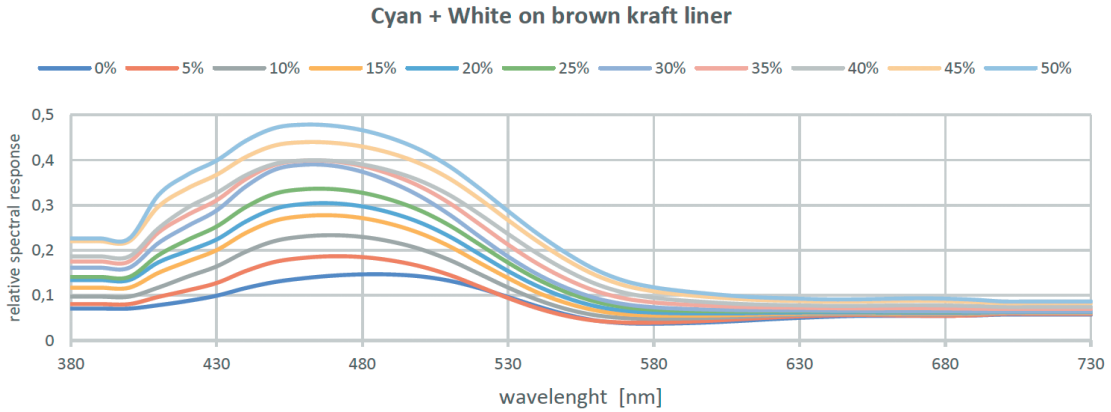


» **Figure 3:** *Variations in CIELCh colour differences (ΔL*, ΔC^*_{ab} and $\Delta h°_{ab}$) of Cyan ink formulations printed on brown kraft liner as a function of opaque white ink dilution percentage (0%-50%). Incremental addition of opaque white ink to the Cyan formulation leads to progressive decrease in both lightness (ΔL*) and chroma (ΔC*), indicating a reduction in overall colour brightness and saturation, while the hue angle difference (Δh) exhibits slight fluctuations across the dilution range*

Sample	White ink content [w/w %]	Viscosity ISO 2431 [sec]	Optical density	L*	a*	b*	C*	h*	ΔE_{00}
Cyan-0	0	20	1,36	31,38	-10,98	-18,96	21,91	239,91	21,87
Cyan-5	5	20	1,32	32,2	-6,92	-26,49	27,38	255,37	22,13
Cyan-10	1	20	1,28	35,54	-9,1	-29,49	30,86	252,85	18,96
Cyan-15	15	20	1,24	38,17	-10,41	-32,32	33,95	252,14	16,67
Cyan-20	20	20	1,22	40,08	-11,79	-33,19	35,22	250,45	14,92
Cyan-25	25	20	1,19	42,06	-12,95	-34,42	36,78	249,38	13,25
Cyan-30	30	20	1,17	43,71	-12,62	-38,01	40,05	251,64	12,43
Cyan-35	35	20	1,12	45,98	-15,01	-35,98	38,99	247,35	10,39
Cyan-40	40	20	1,08	47,85	-17,09	-33,56	37,66	243,01	9,07
Cyan-45	45	20	1,03	50,51	-17,97	-33,99	38,45	242,13	8,38
Cyan-50	50	20	1,00	52,19	-18,34	-35,27	39,76	242,53	8,35



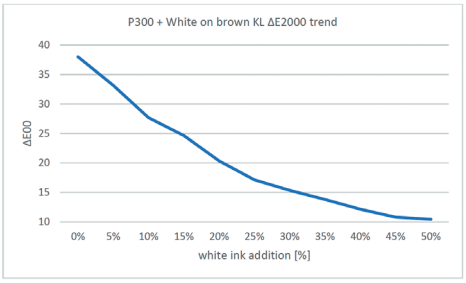
» **Figure 4:** *Spectral reflectance curves of Cyan ink formulations across visible spectrum printed on white substrate*



» **Figure 5:** *Spectral reflectance curves of same Cyan ink formulations printed on the brown kraft liner*

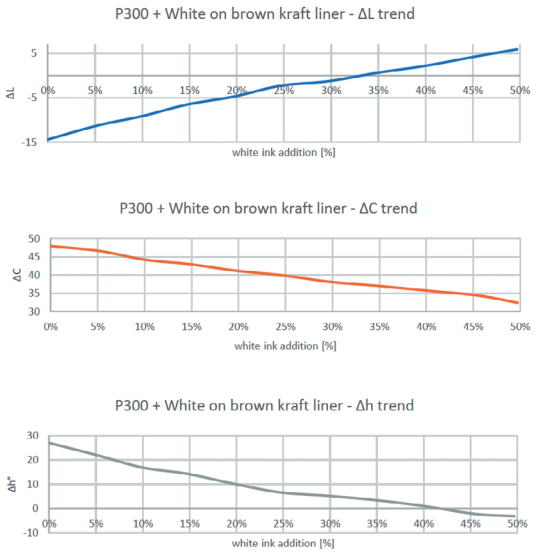
3.5. Influence of opaque white ink addition on Pantone colour

The corresponding physical, rheological and colorimetric parameters for spot colour Pantone 300 across all dilution's levels are presented in Table 7. As shown in Figure 7, the incremental addition of opaque white ink to the Pantone 300 formulation results in a steady increase in lightness (ΔL*), with values shifting from negative to positive, accompanied by a consistent decrease in chroma (ΔC*) and hue-angle difference (Δh).



» **Figure 6:** *Colour difference of Pantone 300 formulations as function of opaque white ink addition when printed on the brown kraft liner*

The ΔL*, ΔC*, and Δh values were calculated relative to the corresponding Pantone 300 reference standard.

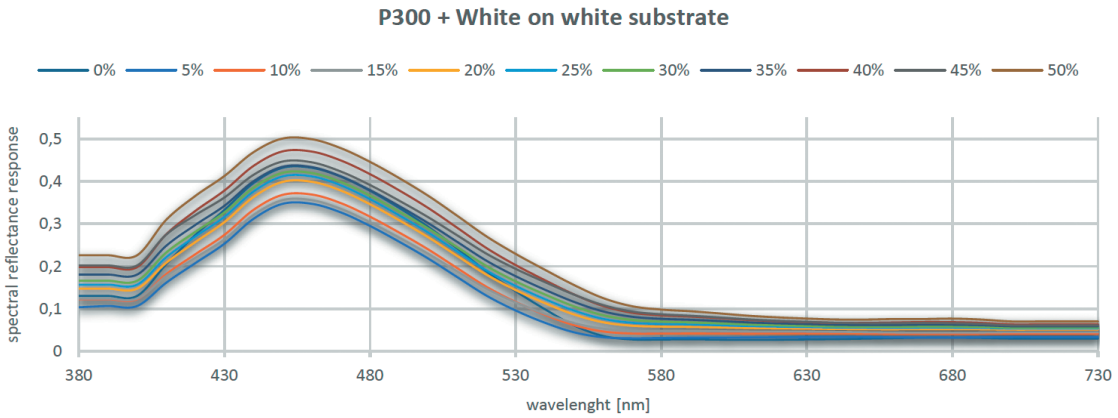


» **Figure 7:** *Variations in CIELCh colour differences (ΔL*, ΔC^*_{ab} and $\Delta h°_{ab}$) of Pantone 300 (P300) spot ink formulations printed on brown kraft liner as a function of opaque white ink percentage (0%-50%)*

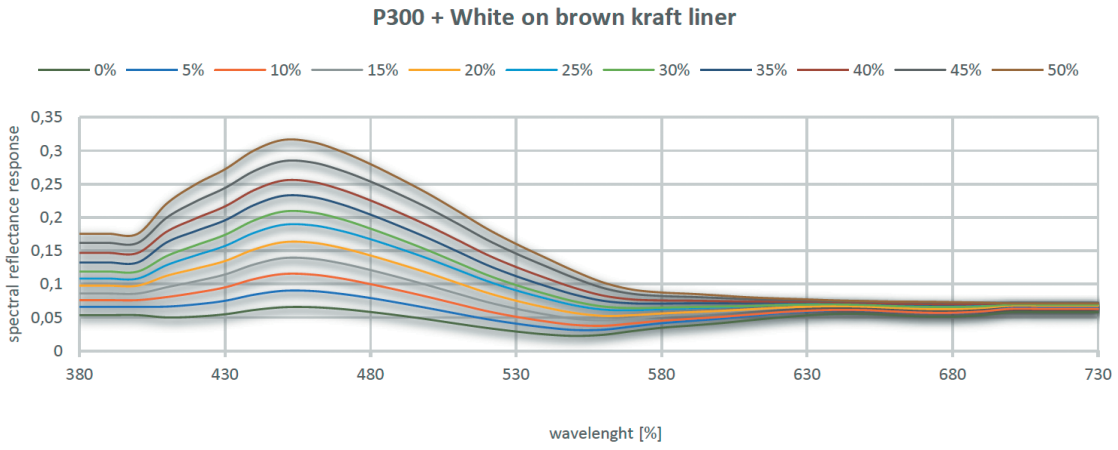
Table 7

Rheological, physical, and colorimetric characteristics of modified Pantone 300 formulations printed on brown kraft liner

Sample	White ink content [%]	Viscosity [DIN 4, sec]	Optical density	L*	a*	b*	C*	h*	ΔE_{00}
P300-0	0	20	1,31	22,09	11,02	-12,49	16,65	311,41	38,01
P300-5	5	20	1,26	25,24	9,00	-15,63	18,04	299,95	33,15
P300-10	10	20	1,24	27,35	6,83	-19,21	20,38	289,58	27,68
P300-15	15	20	1,2	29,92	5,53	-20,85	21,57	284,87	24,65
P300-20	20	20	1,19	31,78	3,15	-23,19	23,41	277,73	20,35
P300-25	25	20	1,17	34,15	1,02	-24,62	24,64	272,37	17,13
P300-30	30	20	1,17	35,19	0,02	-26,44	26,44	270,04	15,35
P300-35	35	20	1,14	37,06	-1,22	-27,52	27,55	267,46	13,81
P300-40	40	20	1,13	38,65	-2,94	-28,68	28,83	264,15	12,15
P300-45	45	20	1,12	40,81	-5,3	-29,71	30,17	259,89	10,81
P300-50	50	20	1,1	42,36	-6,23	-31,52	32,13	258,81	10,45



» **Figure 8:** *Spectral reflectance curves of Pantone 300 ink formulations across visible spectrum printed on white substrate*



» **Figure 9:** *Spectral reflectance curves of same Pantone 300 ink formulations printed on the brown kraft liner*

This trend indicates that increasing white ink dilution enhances the overall lightness of the printed colour while reducing colour saturation and the hue deviation relative to the reference.

3.6. Comparative analysis: Process vs. Spot colour behaviour

A comparative evaluation between process Cyan and spot colour Pantone 300 reveals critical optical and physical behavioural difference when modified with opaque white ink:

Rheological and physical dynamics: Across all addition levels (0-50%), the outflow viscosity remain constant at 20 s (DIN 4 cup). However, wet film density exhibited a linear decrease with increasing white ink concentration – falling from 1.36 to 1.00 for Cyan and from 1.31 to 1.10 for Pantone 300. This drop in density reflects the progressive dilution for the primary colorant pigments by the white formulation vehicle.

Initial substrate shift: Unmodified Pantone 300 printed on both kraft liner (P300-0) suffered significantly higher initial colour distortion (ΔE_{00} = 38.01) compared to Cyan (C-0, ΔE_{00} = 21.87). the brown fibre undertone shifted the chromatic coordinates of Pantone 300 strongly into a positive a* domain (+11.02), severely destroying its blue identity.

Colour difference mitigation (ΔE_{00} trajectory): Both ink sets demonstrated a continuous reduction in total colour difference as opaque white ink concentration increased up to 50%. However, Pantone 300 responded with higher overall error reduction magnitude (ΔE_{red} = 72.5% dropping from 38.01 to 10.45) compared to process Cyan (ΔE_{red} = 61.80% dropping from 21.87 to 8.35).

3.7. Optimal white ink addition

Analysing the trade-off between chromaticity recovery, lightness gain (L*), and colour dilution establishes distinct operational zones for flexographic printing on brown kraft liner:

- Low addition range (5-15%): Insufficient TiO2 light-scattering efficiency. Although lightness increases (L* rises from 31.38 to 38.17 for Cyan, and 22.09 to 29.92 for Pantone 300).
- Effective addition range (20-35%): Provides substantial masking of the brown background. For Cyan, ΔE00 drops below 11.0, while Pantone 300 successfully restores its negative a* coordinate at 35% addition (shifting from +11.02 to-1.22), recovering its true cyan-blue chromatic direction.
- High addition range (40-50%): Yields the lowest overall colour difference relative to reference standards (ΔE00 ≈ 8.35 for Cyan and ΔE00 ≈ 10.45 for Pantone 300). At 50% white ink addition, Cyan lightness (L* = 52.19) perfectly matches the target reference lightness obtained on white double-coated testliner (L* = 52.26). However, additions in this range cause noticeable "pastelisation" and desaturation, which must be balanced against design target specifications.

4. Conclusions

The results demonstrate a significant improvement in the colour accuracy characteristics of inks printed on brown kraft paper when opaque white ink is added to the ink formulation. These findings indicate that controlled addition of opaque white ink may represent an effective technological approach for improving colour reproduction accuracy in printing on kraft-based substrates.

4.1. Main findings

This study demonstrated that the direct incorporation of an opaque white water-based flexographic ink into Cyan process ink and Pantone 300 spot ink provides an effective technical approach to mitigate the strong optical interference caused by brown kraft liner substrates. Without modification, both inks suffer from substantial colorimetric degradation due to selective light absorption by the unbleached kraft fibers, resulting in unacceptably high initial colour deviations (ΔE_{00} = 21.87 for Cyan and ΔE_{00} = 38.01 for Pantone 300) relative to target reference standards.

Progressive addition of TiO2-based opaque white ink systematically increases substrate masking, elevates ΔL* (lightness), and shifts chromatic coordinates towards their true hue directions, successfully eliminating unwanted brown/yellowish undertones.

4.2. Effect magnitude

The addition of opaque white ink yields significant and quantifiable improvements in colour reproduction accuracy across both process and spot ink formulations:

For process Cyan, incremental additions up to 50% reduce the total colour difference from ΔE00 = 21.87 down to 8.35 (a 61.80% overall reduction in colour difference). At 50% white ink concentration, the lightness (ΔL* = 52.19) achieves an exact match with the baseline target printed on white double-coated testliner (ΔL* = 52.26).

For Pantone 300, the modification exhibits a higher magnitude of correction, reducing ΔE00 from an initial 38.01 to 10.45 (a 72.50% reduction of colour difference). Crucially, a 35% addition level is required to recover the negative Δa* coordinate (Δa* =-1.22), effectively restoring the blue-cyan chromatic orientation of the spot colour.

While outflow viscosity remained constant at 20 sec (DIN 4 cup) across all addition levels, wet film optical density decreased linearly (from 1.36 to 1.00 for Cyan, and 1.31 to 1.10 for Pantone 300) due to colorant pigment dilution by the white vehicle.

4.3. Technological implication

From an industrial flexographic perspective, direct modification of process and spot inks offers three primary operational regimes:

- Low addition range (5–15%): Provides insufficient opacity to mask unbleached fibers, resulting in minor lightness shifts without adequate chromatic correction.
- Effective operational range (20–35%): Delivers optimal optical compensation by restoring the true chromatic vector (Δa* and Δb*) while avoiding excessive pigment dilution or target pastelisation.
- High addition range (40–50%): Achieves the lowest absolute ΔE00 values and maximum lightness recovery, but causes noticeable hue desaturation and pastel effects.

This method presents a viable, cost-effective alternative to applying a separate opaque white underlayer in high-volume corrugated board and flexographic packaging production. By eliminating the need for an additional printing unit, additional flexographic plate, and extra printing pass, packaging converters can significantly optimize production efficiency, reduce material consumption, and lower operational overhead while ensuring satisfactory colour consistency on kraft substrates.

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