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Enhanced color density from high-viscosity inkjet inks

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Abstract Inkjet printing inks are typically limited to low viscosities, employing highly dilute inks with low pigment loading compared with inks for other printing processes. This reduces color intensity, limits productivity, and requires higher drying energy. This study compares standard-viscosity graphic inkjet inks (~13 mPa.s shear viscosity) with higher-viscosity inkjet inks (~60 mPa.s), traditionally considered outside the normal jetting range, for print outcomes on corrugated cardboard with both white coated and brown uncoated liners. Higher-viscosity inks imparted greater color density to the print; this was assessed as being due to both the inherently higher viscosity of the ink reducing penetration into the substrate and the higher pigment loading capable of being contained within these inks. While standard-viscosity inks tended to plateau in color intensity as ink coverage was increased, higher-viscosity inks could increase in intensity throughout the entire coverage range on coated white liner. This effect was dependent on the substrate, with the coated white liner exhibiting up to a 67% increase in maximum color density but the uncoated brown liner showing up to a 13% increase. It is envisaged that wider adoption of higher-viscosity inks can increase both color intensity and printing speed, thus making inkjet more competitive with conventional printing processes.

Keywords Inkjet printing, Color, Absorption, Viscosity

Introduction

Inkjet printing is growing in application in sectors such as packaging,[1] textiles[2,3] and ceramics[4] that have traditionally been the preserve of conventional printing processes such as flexography, gravure printing and screen printing. Inkjet permits short-run customizable products with practically zero changeover time or cost between jobs, reduced waste and the process is not reliant on a mask or image carrier.[5,6] However, a current limitation of inkjet printing is the low viscosity of the inks that are capable of being jetted and a very narrow window of physical properties that permit jetting.[2,6–9] Typical viscosities quoted are from single numbers of mPa.s to around 30 mPa.s,[8] with upper limits of around 20 to 40 mPa.s[5,8] depending on the surface tension and density of the ink. For this reason, inkjet inks tend to be highly diluted in comparison with inks used in traditional processes which means substantially lower pigment, or active material loading in the case of functional inks, resulting in a much thinner printed ink layer and a greater volume of ink, and therefore carrier, to achieve a target color density. Coupled with this, drop-on-demand inkjet inks tend to be relatively slow drying to prevent the ink drying in the nozzles.[5,6,10] The printer must either tolerate a smaller color gamut and less intense colors or effectively overprint several times to achieve the same target color/thickness that can be routinely achieved by other processes. This leads to a second limitation of inkjet, which is the relatively low print speed which

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reduces productivity and competitiveness with other processes. The dilute nature of the ink imposes an increase in drying time, which again reduces productivity and adds a further energy cost for driving the solvent from print.[10] Furthermore, the low ink viscosity of the inks results in greater penetration into an absorbent substrate, and this penetration reduces the color intensity of the print further.[1,11]

From a fluid dynamics perspective, inkjet printing is a highly complex process, with factors on both the print head and substrate side affecting the printed product. These include the flow inside the printhead, formation of air bubbles, the actuation process, meniscus behavior at the nozzle, wetting of the nozzle and jetting behavior. From the substrate perspective, droplet impact, droplet merging, wetting and absorption, evaporation and drying must be considered.[12] Printing of higher-viscosity inks remains a fundamental challenge for the inkjet industry, as such inks are inherently more difficult to successfully jet and maintain reliable performance over time without clogging the inkjet nozzles. To provide an approximate indication of the suitability of an ink for jetting, the mechanics of drop formation can be approximated by the dimensionless number Z (Equation 1), the reciprocal of the Ohnesorge number, which factors in nozzle diameter (d), fluid density (ρ), surface tension (γ) and viscosity (η). Z ranges for stable drop formation have been quoted previously[10,13,14] as sitting within the range $1 < Z < 10$. An increase in viscosity results in a decrease in Z, with more energy required to eject the droplet, and ink ejection eventually becoming impossible due to viscous dissipation, where the work done by the fluid is transformed into heat, and a greater risk of nozzle clogging occurs. The upper limit of Z, which is of less concern in this context, results in uncontrolled droplet formation in the form of undersized satellite droplets.[5,13]

$$Z = \frac{\sqrt{d\rho\gamma}}{\eta} \tag{1}$$

While various methods have been reported for direct-write noncontact techniques for depositing high-viscosity inks, these are not typically in the form of the drop-on-demand piezoelectric systems which are most used in industrial inkjet applications. Piezoelectric inkjet printing is considered the most mature and reliable form of the technology with an abundance of available ink formulations, while alternatives are typically still under development, not yet commercially viable, and suffer from slow print speed.[15] Reports of high viscosity capabilities for jetting systems include the use of a pneumatic needle jetting valve for 3D printing of nano-sliver inks,[16] laser-induced jetting for fluids up to 210 mPa.s,[17] laser-induced forward transfer for adhesives up to 1700 mPa.s,[18] electrohydrodynamic-jet printing for silver nanoparticle inks up to 4000 mPa.s[19] and pneumatic aerosol jet deposition with a maximum quoted viscosity of 1000 mPa.s[20]. Reported jetting systems that do fit into the piezoelectric drop on demand category are usually presented in the laboratory setting and are at the prototype stage, with a focus in literature on jetting of droplets rather than print outcomes. Bernasconi et al.[5] reported jetting of glycerine-water solutions with viscosities in excess of 200 mPa.s using a prototype drop-on-demand piezoelectric printhead. Issues were reported with drop velocity and satellite drop formation for high-viscosity solutions, and when suspensions were used, namely a ZnO nanoparticle suspension and a diluted PEDOT:PSS commercial ink, the reported viscosities were much lower at 8.58 and 34.83 mPa.s, respectively (at a shear rate of 100 s^{-1}). Wang et al. reported a bespoke piezoelectric printhead capable of printing up to 98.17 mPa.s using a single glass nozzle[21] and Pinto et al. reported a custom single-nozzle piezoelectric printhead for fluids up to 60 mPa.s.[22] Commercial single drop piezoelectric dispensers are available from suppliers such as Microdrop Technologies GmbH,[23] and MicroFab Technologies, Inc.[24] In summary, printing of highly viscous inks via drop-on-demand inkjet remains a challenge in terms of print speed, production volume and technical issues with delivering the inks which is preventing commercial exploitation[5,15] and this has not permitted proper evaluation of potential benefits to color reproduction or productivity from such inks.

Recent advances in commercial inkjet printhead technologies are claimed to be able to deposit inks with jetting viscosities of up to 100 mPa.s.[25] Further to this, ink heating can also be used in this system to reduce the viscosity of the ink in the print head, which reportedly permits room temperature viscosities in excess of 100 mPa.s, with an upper room temperature viscosity limit of 1000 mPa.s quoted.[25] Although heating can be used to reduce the effective viscosity of an inkjet ink, there are practical limits since excessive heating can cause thermal damage to the ink.[5]

Given the availability of technologies for higher-viscosity ink deposition and the potential benefits to both print color reproduction and productivity, a comparison was made in this study of printing and colorimetric outcomes between inkjet graphic inks of standard jetting viscosity and specially developed inks with higher viscosities, above what is conventionally accepted as jettable in commercial inkjet. Ink viscosity, surface tension and wetting were measured, then the inks were printed on a commercial corrugated cardboard substrate with both white coated and brown (test) liners using a commercially available inkjet head capable of handling higher-viscosity inks.

Materials and methods

Inks and substrates

The inks used in the study comprised standard-viscosity inks in the typical inkjet viscosity range and higher-viscosity inks outside the normal window for printability made specially for this study. The inks were water-based cyan pigmented and were provided by Nazdar Limited, Stockport, UK, as detailed in Table 1.

A first set with both a standard-viscosity (SV1) and high-viscosity ink (HV1) and a second set again with both a standard-viscosity (SV2) and high-viscosity ink (HV2), but with higher pigment loading than the first set were provided. Pigment loading and density values were specified by the manufacturer and are as listed in Table 1. A fixed pigment to binder ratio was used for all inks and the same pigment type was used throughout. Both pigment content and the type of binders used were varied to change the viscosity.

In terms of substrate selection, paper board products are widely used in packaging as they protect the product from damage and contamination while serving an additional purpose in terms of communication or advertising via printing.[26,27] They must also cope with the relatively high water content of the inkjet ink which can cause fiber swelling.[28] The substrate used in the study was a commercial corrugated cardboard sheet as detailed in Table 2. One face comprised a coated white liner, and the other a so-called Test liner comprised of recycled brown paper. For comparison, both faces were printed on. The two faces of the substrate had different liquid absorption characteristics to one another.

Characterization of inks and substrates

A stress-controlled rheometer (Malvern Kinexus Pro) was used to assess the viscosity of the inks. A 50-mm-diameter stainless steel cone and a parallel plate were used to measure the shear viscosity of the samples, with a solvent trap to reduce solvent loss to the environment. The inks were first ramped from 1 to 200 s^{-1} to ensure a consistent preshear across all samples. Equilibrium viscosity measurements were then taken over a 30 s time period at shear rates of 10, 25, 50, 75, 100, 150, and 200 s^{-1}. To evaluate the effect of heating on viscosity, separate tests were performed at temperatures of 20, 25 and 35 °C using a Peltier plate system to cover the anticipated range of ink temperatures required for printing.

The surface tension of the inks was evaluated using the pendant drop method using a 10 μL drop size. The contact angle and drop volume of water were measured on both white and brown liners using the sessile drop method with a 2 μL drop size and elliptical fit method. Both sets of measurements used a Krüss DSA30 Drop Shape Analyser.

Table 1: Pigment loadings and densities for inks used in the study

Ink name	Pigment loading (wt%)	Density (g/mL)
SV1	3.5	1.13
HV1	4.3	1.10
SV2	4.1	1.13
HV2	6.3	1.13

Printing methodology and characterization of printed samples

Equipment used

The main components of the printing system were the inkjet head, the ink management system that circulated the ink through the head and managed its temperature, and a moving platen on which the substrate was placed. The components were combined on a specially built platform (Fig. 1). The key print settings are summarized in Table 3. The ink was circulated through the print head using an HV fluid management system, Megnajet (Kettering, UK). Printing was carried out using a Xaar Aquinox GS6 drop-on-demand piezoelectric printhead provided by Xaar (Cambridge, UK). A specially constructed platen system was used, with bed movement controlled by a controller board (Duet 3 Mainboard 6HC).

A single printhead was used to print an image of 70.5 mm width, corresponding to the width of the rows on the print head. To provide a range of color coverages for comparison, the inkjet head was able to print at 7 different grey levels (8 total grey levels including bare substrate as level 1). The grey levels

Table 2: Substrate used in the study

Product description	White cardboard sheets 297 mm x 210 mm A4 single wall				
Supplier	Europa Industries, UK				
Product number	AB20345/50 MPN: ABSWW				
Designation	125 W/T B-flute				
Liners	White 125 gsm, Test 125 gsm				
Flute	B				
Measured color D50/2°		Cyan density	L*	a*	b*
	White	0.10	91.00	0.49	−1.21
	Test (brown)	0.42	62.95	8.53	17.47

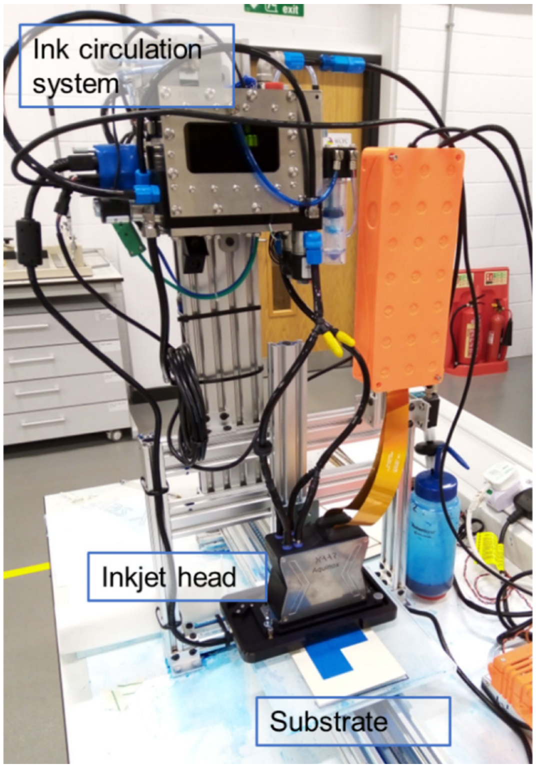

Fig. 1: Printing equipment used in the study

Table 3: Key printing parameters

Parameter	Value
Grey levels	1 to 8 (0 to 7 droplets per dot)
Print width	70.5 mm
Number of rows	4
Nozzles per row	500
Nozzle resolution (4 rows)	720 dpi
Firing frequency	3 kHz
Print speed	6.35 m/min

were achieved by using differing numbers of ink droplets per printed dot (dpd) ranging from 1 to 7, with droplets combining in flight to produce various sized dots on the substrate. The printer employed 4 rows of 500 nozzles to give a total print resolution of 720 dpi (dots per inch). A further comparison was achieved by employing fewer rows and with 2 rows only or 1 row only, the resolution across the width of the printhead could thus be reduced to 360 and 180 dpi, respectively, but with fixed 720 dpi in the print direction. All rows were offset from one another to give even coverage. The inkjet head allowed 21 different coverage levels to be evaluated per ink (3 head combinations with 7 grey levels). A test pattern was used with 8 grey levels (bare substrate as level 1—Fig. 1) on a 2000 by 4000 dot footprint (70.5 by 141 mm). Using a print frequency of 3 kHz a bed speed of 6.35 m/min was required. A specific waveform was provided for each ink and the primary means of adjusting ink deposition was then drive voltage and ink reservoir temperature (via the fluid management system), with increases in both parameters giving an increase in droplet size. Voltage and temperature were adjusted in combination to achieve sufficient print quality, without defects and nozzle blocking. Once printed, samples were allowed to dry at ambient temperature overnight before analysis. Printing was carried out in a temperature-controlled laboratory at 19 °C.

Evaluation of ink deposit volume

To provide a standardized means of comparison between the different inks, accounting for differences in droplet sizes across the range of inks, the coverage of the prints was calculated in terms of grams per square meter (gsm) of wet ink deposited at given grey levels. Inks were deposited into petri dishes containing blotting cotton and ink mass was weighed at various grey levels. A 720 dpi solid block image of 2000 x 4000 dots (70.5 x 141 mm) was used and multiple repeat print cycles were used to ensure that each mass test had at least one gram of ink deposited per mass measurement. Dishes were weighed before and immediately after printing using a mass balance accurate to 1 milligram. The mass of ink per print was then used to calculate a wet gsm value.

Color measurement and imaging of printed samples

For a simple visual comparison, scans of the prints were taken using a desktop scanner. The color of the printed samples was then measured in terms of cyan density and CIE L*a*b* (Commission Internationale de l'Eclairage) using an X-rite eXact$^{\mathrm{TM}}$ 0/45° reflectance spectrophotometer with D50 illuminant and 2° observer. Five prints were made for each row number/substrate combination, with 3 measurements taken per printed patch, giving a total of 15 color measurements per grey level/row number/substrate combination. Microscope imaging of selected print samples was carried out using an Alicona Infinite Focus G5 microscope (Alicona Imaging GmbH).

Results

Ink viscosity and surface tension

Equilibrium ink viscosity values at 100 s^{-1} are presented at test temperatures of 20 °C, 25 °C and 35 °C in Fig. 2. Full viscosity data are provided in supplementary material as plots of equilibrium shear viscosity

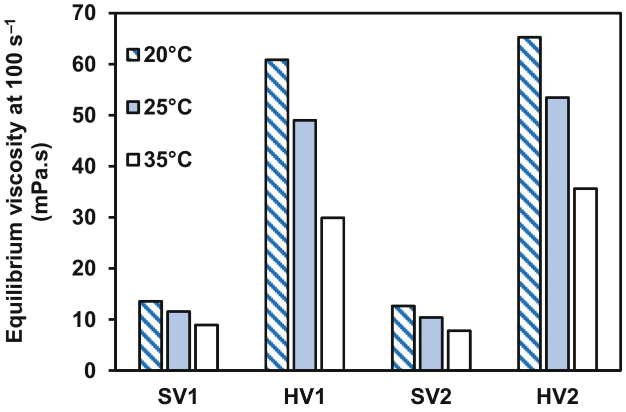

Fig. 2: Equilibrium viscosities of inkjet inks at shear rate of 100 s^{-1} at various test temperatures

vs. shear rate (with 10 repeat measurements taken per shear rate). The inks showed no thixotropic effects over the time periods and shear ranges used (10 to 200 s^{-1}). The standard-viscosity inks showed near Newtonian response, with viscosity practically constant relative to shear, while the higher-viscosity inks showed a slight shear thinning characteristic. At a shear rate of 100 s^{-1}, the standard-viscosity inks were of the order of 13 mPa.s at 20 °C, while the higher-viscosity inks were of the order of 61 to 65 mPa.s, which is outside the range.[5,8] Upon increasing the testing temperature, the viscosity was reduced significantly, particularly for the higher-viscosity inks; with HV1 falling from 60.9 mPa.s at 20 °C to 29.9 mPa.s at 35 °C, and HV2 falling from 65.3 mPa.s at 20 °C to 35.0 mPa.s at 35 °C. This demonstrates the potential for inkjet inks to be significantly reduced in viscosity with heating.

The shear rate of the inkjet process is much higher than the 10 to 200 s^{-1} shear rate used in testing the inks. Common practice is to extrapolate the viscosity data to more relevant shear rate ranges, and Derby and Reis[13] propose that a 1–10 kHz operating frequency translates to an approximate strain rate of 10^3 to 10^4 s^{-1}. Given that the standard-viscosity inks gave a flat response to shear, a simple extrapolation of the data to 3000 s^{-1} shear rate range (3 kHz printing frequency) using an exponential decay, gives estimated 20 °C viscosities of 13.2 and 12.4 mPa.s for SV1 and SV2, respectively, which are close to the 100 s^{-1} values. The slight shear thinning evident in the high-viscosity inks results in extrapolated viscosities of 55.6 and 57.6 mPa.s for HV1 and HV2, respectively, a small reduction when compared to the 100 s^{-1} values (Fig. 2).

The surface tensions for the inks, as measured using the pendant drop method, are shown in Table 4 (10 drops made per ink and 5 measurements per drop over 10 s ($n = 50$)). The surface tensions were broadly similar for all four inks and were in the 32.7 to 34.9 mN/m range, with the higher-viscosity inks having slightly higher surface tensions than their standard-viscosity counterparts. The surface tension, viscosity, and ink density were used to estimate indicative Z values for the inks as shown in Table 4 (standard deviations for viscosity and surface tension are shown). The standard-viscosity inks gave Z values comfortably within the acceptable range[13] at 2.30 and 2.46, but the high-viscosity inks gave Z values below 1 (at 0.52 and 0.49), which is indicative of excessively viscous inks that would not traditionally considered to reliably jet.[13]

Table 4: Viscosity, surface tension and indicative Z value at 20 °C

Ink name	Viscosity (mPa.s at 100 s^{-1})	Surface tension (mN/m)	Indicative Z value
SV1	13.5 ± 0.018	32.84 ± 0.035	2.30
HV1	60.9 ± 0.049	34.85 ± 0.046	0.52
SV2	12.6 ± 0.010	32.74 ± 0.060	2.46
HV2	65.3 ± 0.130	34.45 ± 0.035	0.49

Substrate wetting characteristics

The contact angle and drop volume of 2 μL drops of deionised water on both coated white and brown liners are shown in Fig. 3. Substantial differences in wetting and absorption were observed between the different liners. The coated white liner showed a constant drop volume over the measurement period of 20 s, while contact angle fell slightly initially but then plateaued at 100°. In contrast, the brown liner showed a rapid reduction in both drop volume and contact angle, volume falling from ~ 2 to ~ 0.5 μL and contact angle falling from ~ 105° to ~ 25° over 20 s.

The contact angles of the inks are compared on both liners in Fig. 4, together with top-down photographs of ink drops after deposition (taken using a desktop scanner). Sample images of droplets on the liners taken by the Drop Shape Analyser are shown in supplementary materials. The high-viscosity inks showed higher contact angles than the standard-viscosity inks. Despite having similar viscosity and surface tension, the HV2 ink showed a lower contact than the HV1 ink. Ink droplets spread to a greater extent on the brown liner than on the white liner, and standard-viscosity inks spread to a greater extent than the high-viscosity inks. Inks from set 2 (SV2 and HV2) spread more than inks from set 1 (SV1 and HV1). Due to the fiber structure of the cardboard liners, deposited drops tended to spread unevenly making it difficult to obtain accurate drop volume values and resulting in some fluctuation in contact angle data. This effect was more pronounced on the brown liners, where there was higher absorption.

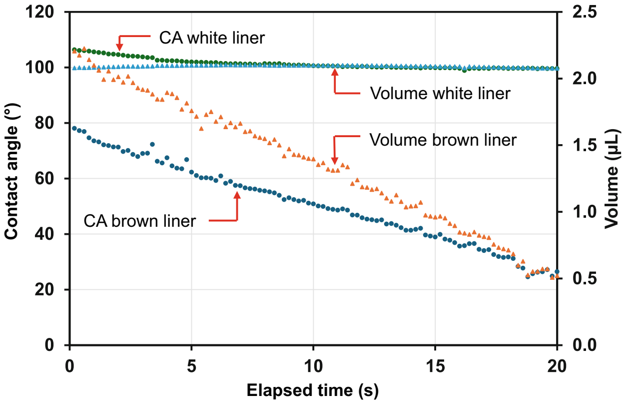

Fig. 3: Contact angle (CA) and drop volume for water on white and brown liners (mean of 5 drops)

Print outcomes

The drive voltages and ink temperatures required to achieve sufficient print quality are listed in Table 5. Increases in drive voltage and temperature resulted in larger drop sizes for a given ink, with insufficient voltage giving poor print quality due to missing dots and eventual drying in the print head. On the other hand, excessive voltage resulted in flooding. Greater drive voltages were required for the higher-viscosity inks to achieve sufficient droplet formation, volume of deposit, and print quality when compared to their standard-viscosity counterparts. However, in all cases drive voltage requirements were well within the maximum 30 V drive voltage of the printhead. Both SV1 and HV1 did not require any heating to achieve acceptable print quality and a temperature of 21.5 °C was recorded at the print head. Both SV2 and HV2 required heating to around 31 °C to achieve acceptable print quality. Based on equilibrium viscosity data at 100 s^{-1} (Fig. 2) and a linear trendline between test temperatures, this gives estimated printing viscosities of 12.9, 57.1, 8.9 and 43.0 mPa.s for SV1, HV1, SV2 and HV2, respectively, at the designated ink temperatures (Table 5). While ink temperature affects shear rheology, there is also an influence on factors such as ink elasticity and surface tension.

Sample ink mass test data are shown in Fig. 5 as plots of grams of wet ink deposited per square meter of substrate (gsm) vs. droplets per dot (analogous to grey level). Data are presented for SV1 and HV1 inks printing with all 4 rows and at different grey levels using the settings described in Table 5. There was a straight-line relationship between grey level (droplets-per-dot) and mass of ink deposited, as there was between number of printheads used and mass of ink. Maximum coverage and estimated droplet size are summarized in Table 5. HV1 gave a slightly larger drop size than SV1, while SV2 and HV2 gave very similar drop sizes to one another but larger than both SV1 and HV1. The mass data were used to standardize the colorimetric data to allow prints to be compared by ink mass deposited.

Scanned images of prints made with the various inks are shown for both white and test liners in Fig. 6. The prints shown used all 4 rows of the print head (720 dpi). For the standard-viscosity SV1 ink on white liner, there was an apparent increase in tone with increased ink deposition at low coverage/gsm, but there was no observable increase in color intensity between mid and high coverage. In contrast, the high-viscosity HV1 ink on white liner showed a building of color intensity throughout the full range of coverage, and a much darker color print than for SV1, especially at higher coverage. When the brown test liner was used, neither the SV1 nor HV2 inks showed much apparent increase in color intensity with coverage, though HV1 gave darker prints than SV1.

For ink set 2, the standard-viscosity ink (SV2) gave similar color intensity across the coverage range for both liners. For the white liner, HV2 showed an increase in color intensity with coverage. As with ink set 1, this effect was less pronounced on the test (brown) liner, although there did appear to be a greater color intensity for the HV2 when compared with SV2, with the difference between high and standard-viscosity prints appearing more significant in ink set 2 than in set 1.

The color of the printed samples is shown graphically as plots of both cyan density and CIE L* vs. grams of wet ink per square meter (gsm) in Fig. 7. All data are presented together, regardless of whether 1, 2 or 4 printhead rows were utilized. To summarize, maximum densities and minimum CIE L* values for the various combinations of ink and liner are compared in Table 6. Data are presented separately for 1, 2 and 4 row printhead rows in supplementary materials, with the addition of CIE a* and b* vs. gsm plots.

Generally, the higher-viscosity inks showed higher density values and lower CIE L* values than the standard-viscosity inks for a given ink volume (gsm). For the white liner, HV1 showed a substantially higher color density than SV1, with a maximum cyan density of 1.72 compared with 1.03 for SV1, representing an up to 60% increase in density. There was also a continual increase in cyan density with HV1 coverages beyond 40 gsm, whereas the density of SV1 plateaued at around 20 gsm, with further increases in ink deposit having no significant effect on the color density. The greater cyan density of HV1 was accompanied with a much lower CIE L* value, again without a plateau at high loading. Similar trends were evident for ink set 2 with HV2 showing a substantially higher color density than SV2 (up to 53% increase in density at high coverage) and also a much lower CIE L*.

The higher-viscosity inks contained more pigment than their lower-viscosity counterparts, yet this can only partially account for their greater color strength on white liner. For context, SV1 and HV1 had pigment loadings of 3.5% and 4.3%, respectively, which represents an increase of around 23%, yet the increases in print density, and tendency not to plateau, were well in excess of what might be expected by a simple ratio of

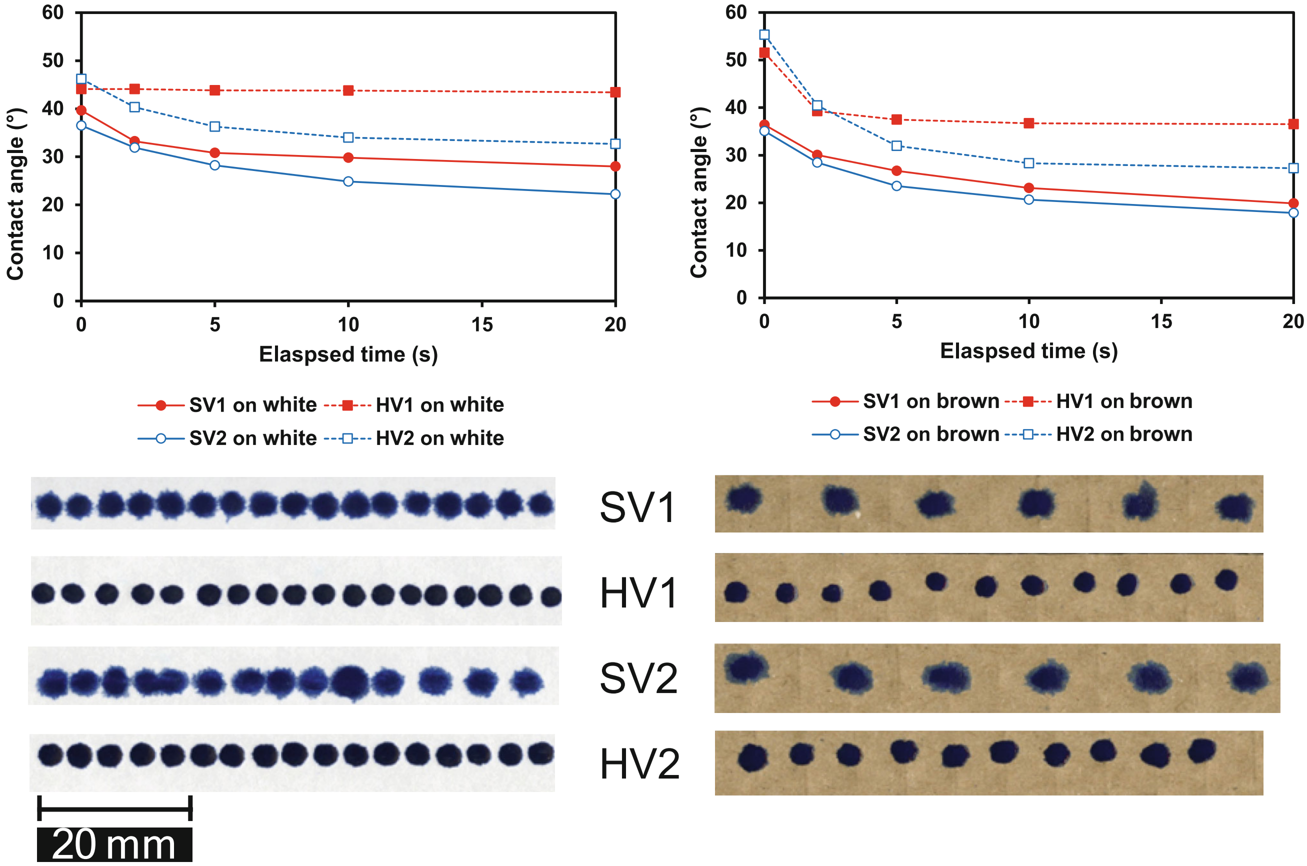

Fig. 4: Contact angle of inks on white and brown liners (top) and photographic images of 2 μL ink droplets on white and brown liners (bottom)

Table 5: Printing parameters and coverage for each ink

Ink name	Drive voltage	Ink temperature (°C)	Approximate viscosity at print temperature (mPa.s at 100 s^{-1})	Maximum coverage (g/m^2)	Droplet size (pL estimated)
SV1	22	21.5	12.9	43.8	6.9
HV1	24	21.5	57.1	47.3	7.6
SV2	23	31.0	8.9	63.6	10.0
HV2	25	31.5	43.0	63.5	10.0

the pigment loading and gsm. Also, SV2 and HV1 had very similar pigment loadings, yet substantially different color, while HV2 had ~ 50% more pigment than HV1 yet had a lower maximum cyan density. Given that the pigment type is the same across the various inks, the maximum densities achieved on white liner appear be primarily due to the viscosity itself, while the higher pigment loadings in SV2 and HV2 gave them higher color densities at the low coverage/gsm end compared with their respective set 1 inks. The densities achieved by the higher-viscosity inks represent a very substantial increase in color density over conventional viscosity inks. When wetting characteristics of the inks were compared (Fig. 4), the higher-viscosity inks were found to spread to less of an extent than the standard-viscosity inks.

The test liner did not show such a strong relationship between ink viscosity and color density. Although there were significant colorimetric differences between the high- and low-viscosity inks on the test liner, the influence of viscosity on color was diminished. The increases in maximum density were 6.5 and 13.6% for HV1 vs SV1 and HV2 vs SV2, respectively. This is due to the greater absorption of liquid by the test liner (Fig. 3) but also a suppression of color intensity from the darker color of the liner.

When the data were analyzed separately for 1, 2 or 4 printheads utilized (supplementary material), there was some scatter at low gsm when using the white liner. Prints produced with a single row (180 dpi across printhead) had a lower density and higher L* than prints of equivalent gsm (i.e., amounts of ink deposited) produced using 2 or more rows. Since only 1 of the 4 rows were utilized, the print was deposited in the form of lines, rather than solid color. This is demonstrated in Fig. 8, which shows microscope images of print made at the lowest grey level (one droplet per drop) and utilizing only one of the four printing rows. There were gaps between tracks of ink, which resulted in substrate show through. Printing with 2 or 4 rows filled the gaps due to the offset of nozzles in different rows, while there was also greater spreading when higher coverages were used. This show through effect was more noticeable with high-viscosity inks, than standard-viscosity inks, and was also more apparent on the white liner than the test liner. For the test liner, there did not appear to be a strong distinction between the spreading of standard and high-viscosity inks which is presumably due to the relatively higher absorptivity of test material. Indeed, the general trend of increased color density for higher-viscosity ink was not always evident when printing with only a single row. This appeared to be due to reduced ink spreading for the high-viscosity ink, compared which standard-viscosity counterparts, which resulted in greater substrate show

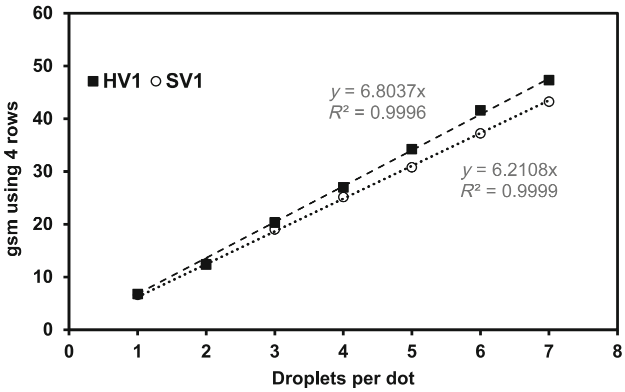

Fig. 5: Mass of ink deposited at different grey levels for SV1 and HV1 inks. Droplets per dot 1 to 7 corresponds to grey levels 2 to 8 (where 1 is the unprinted substrate)

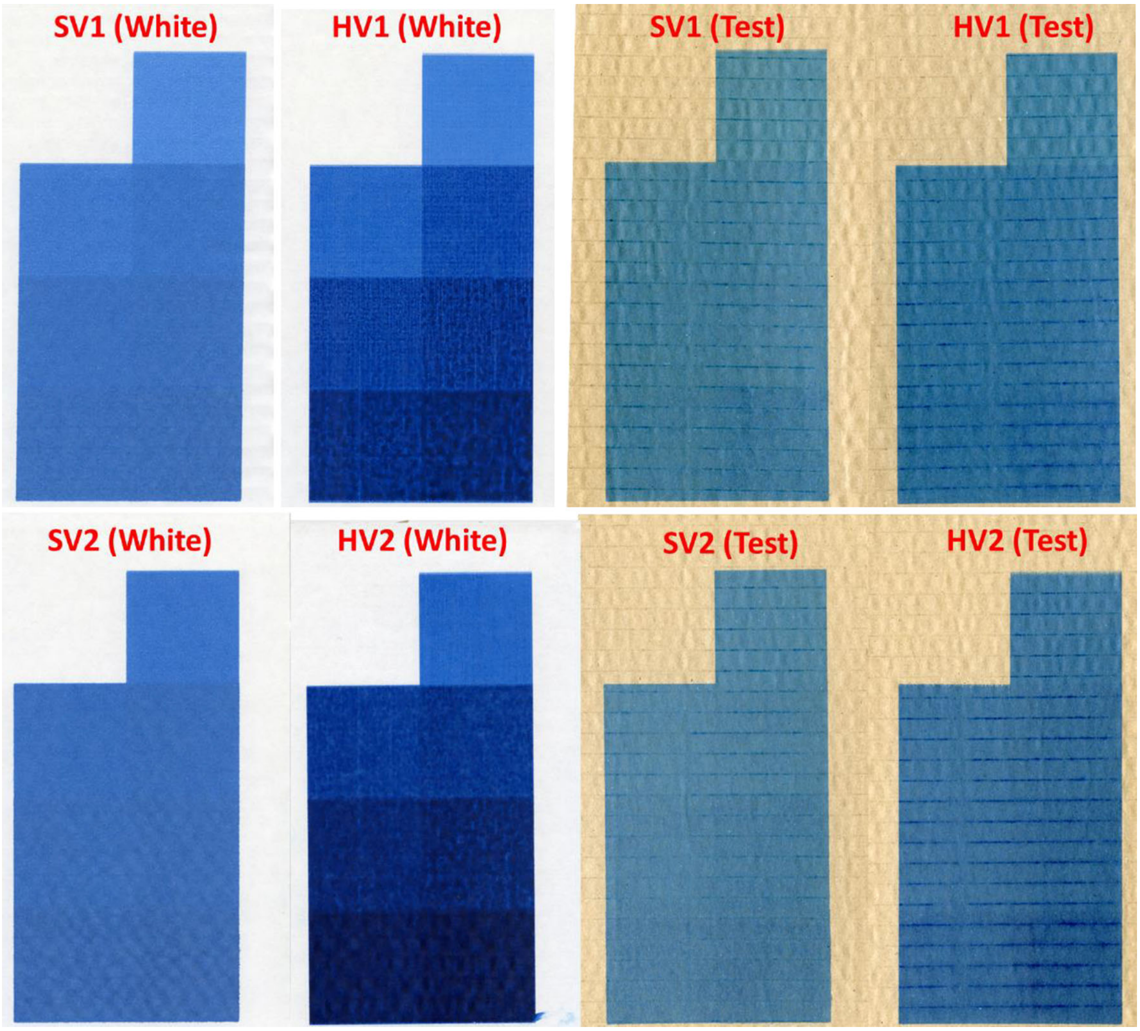

Fig. 6: Scanned images of prints using all 4 rows (720 dpi)

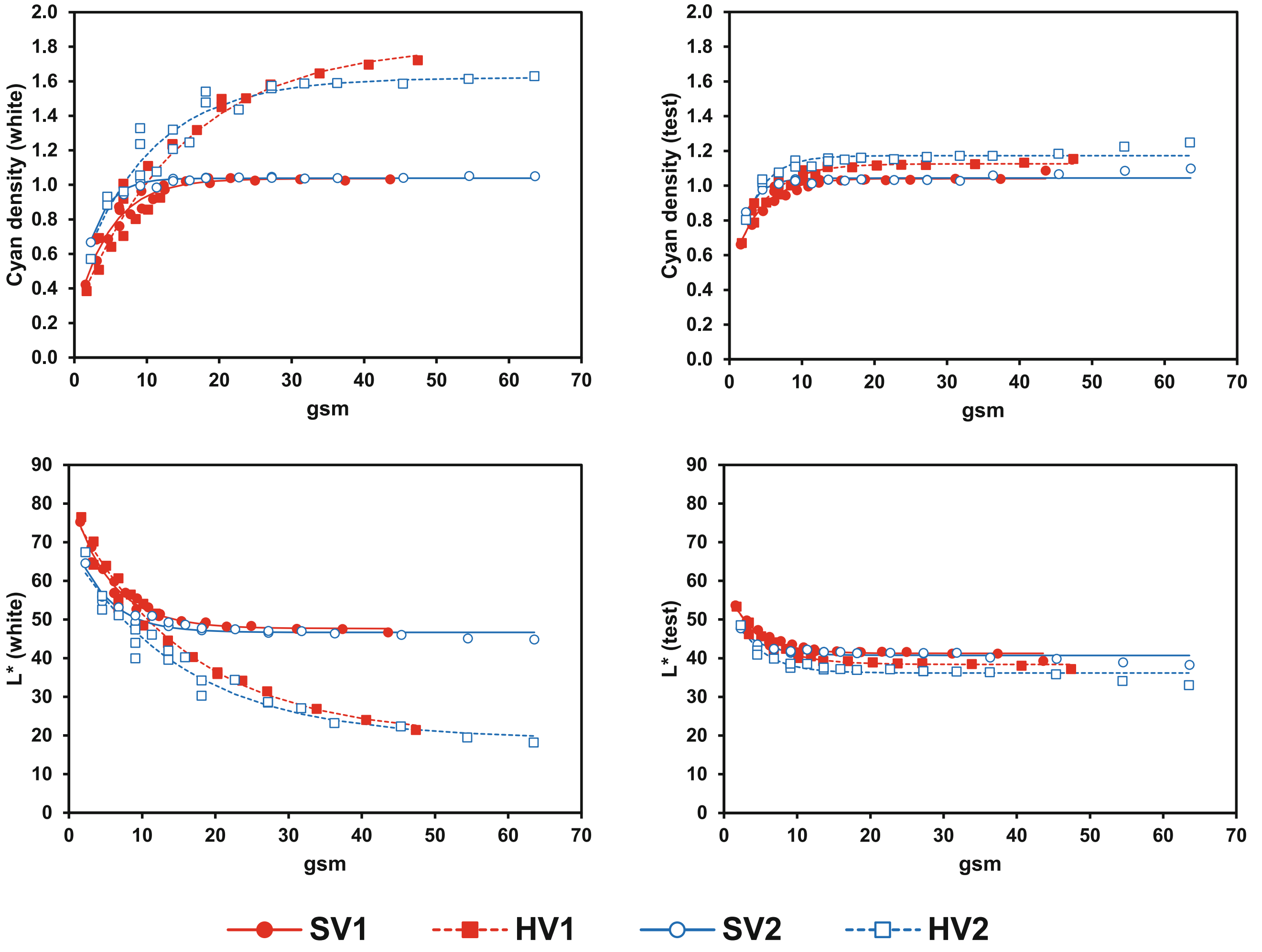

Fig. 7: Comparison of cyan densities and L* of prints using white liner (left) and test liner (right)

Table 6: Summary of maximum cyan density and minimum CIE L* values for the various ink and substrate liner combinations, with percentage change when moving from standard to high viscosity

Ink name	White		Test (brown)	
	Maximum density	Minimum L*	Maximum density	Minimum L*
SV1	1.03	46.7	1.08	39.3
HV1	1.72	21.4	1.15	37.2
% change	+ 67	−54	+ 6.5	−5.3
SV2	1.06	44.8	1.10	38.3
HV2	1.62	18.2	1.25	33.0
% change	+ 53	−59	+ 13.6	−13.8

through, and a reduced color density per gsm compared with prints made with 2 or 4 rows utilised.

Discussion

Inkjet inks of standard viscosity and inks outside the conventionally accepted viscosity for printing were successfully jetted. The higher-viscosity inks required more energy in the form of higher drive voltages, but they were able to produce a greater color density on printed cardboard than standard-viscosity inkjet inks. The two factors that can be exploited to increase color intensity are the viscosity itself, which reduces the absorption of the ink into the bulk of the substrate,[11,29] but also the additional pigment that can be contained within a higher-viscosity ink. Although it is not possible to precisely separate the individual effects of viscosity

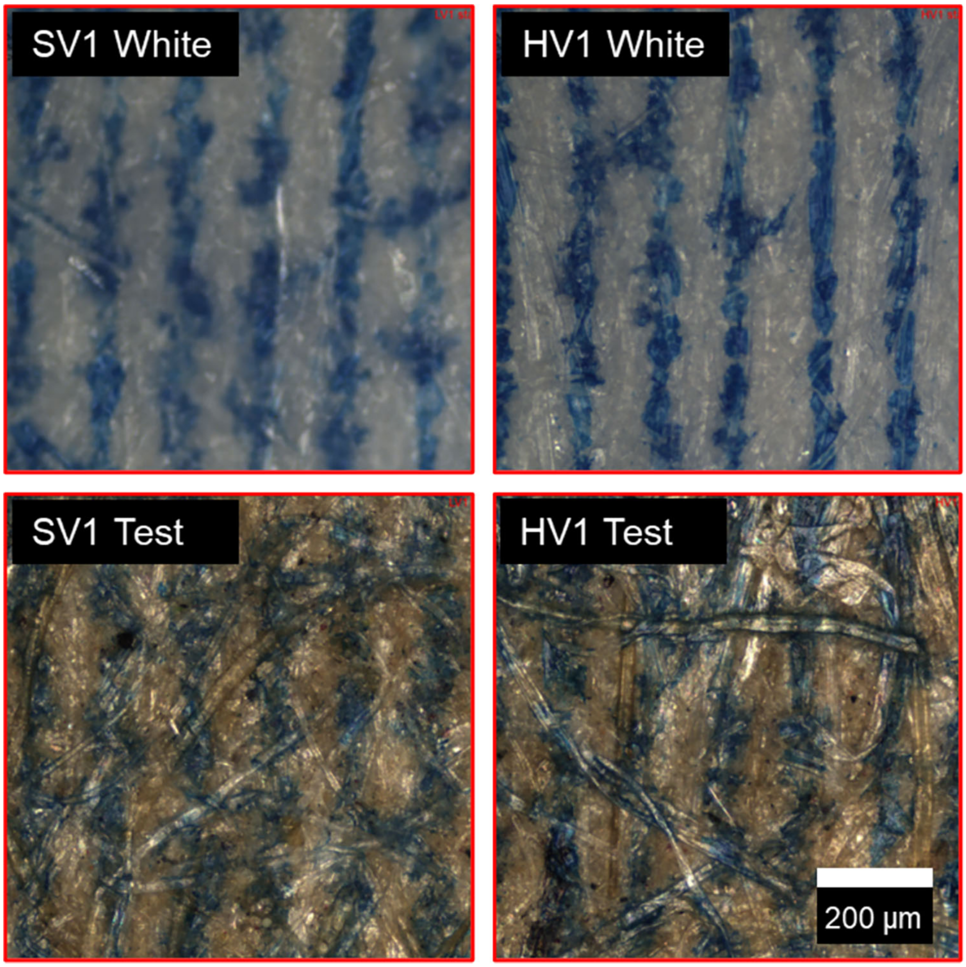

Fig. 8: Microscope images of 1 droplet per dot depositions using 1 row only (180 dpi x 720 dpi) ink set 1 (SV1 and HV1)

and pigment loading, it appears that for the less absorbent white coated liner, the viscosity made a greater contribution to the color of the print than an increase in pigment loading, indeed the HV1 and SV2 had similar pigment loadings (4.3 and 4.1 %, respectively), yet HV1 demonstrated a much higher color density than SV2. Modification of ink viscosity is a potentially lower expense adaptation to the ink than adding extra pigment and could be achieved by substitution of the base polymers. As solid loading of a dispersion is increased, there is an increase in particle-particle interactions, the consequence being an accelerating increase in viscosity with solid loading when following Krieger-Dougherty behavior.[13] These nonlinear rheological behaviors become more significant as more particulate is added to an ink and may have adverse consequences for jetting. However, when viscosity is modified exclusively by the choice of binder, this acceleration effect no longer applies.

Previous studies have demonstrated that increased ink viscosity results in reduced liquid penetration into the bulk of a paper substrate, with viscosity having a more significant effect than surface tension in the viscosity range of the order of 3 to 8 mPa.s,[11] and a study by Waldner et al.[30] showing that a higher-viscosity ink will absorb more slowly, which permits more time for spreading and lateral penetration when a 2.8 to 9.2 mPa.s viscosity range was evaluated. The optical density of the print, and bleed through to the reverse, is strongly influenced by the penetration of the ink in the z-direction, though this depends on the structure of the paper.[29] These studies are within what is considered to be a conventional ink viscosity window, so viscosity related impedance of absorption is amplified in this study by increasing viscosity beyond these limits. While there is higher color intensity for the more viscous inks, there may be some loss of detail in the light tones. This trade-off has been discussed previously[11] and can be mitigated against by use of fewer rows, which again reduces the ink demand. As well as benefits in terms of print color, greater viscosity is likely to reduce lateral spreading of ink and this has the potential to give sharper printed features, especially in absorbent substrates. Although this is not the subject of this paper, other modes of testing are available to assess reproduction of fine features.[31]

Prints made on the coated liner showed a strong distinction between the standard and higher-viscosity inks, but the effect of both viscosity and pigment loading is highly substrate dependent and will be affected by both the absorbency of the substrate and its color. Prints on the more absorbent test (brown) liner showed much lower gains in density with increased viscosity as the ink was more readily soaked into the bulk, rather than sitting on the surface of the substrate. However, in this case, there was still a benefit from increasing pigment loading as evidenced by the higher densities in the HV2 ink. As well as the absorption/penetration of the ink, the use of a darker substrate inherently diminishes the color gamut when compared to a white.[3,32] It should be noted that brown board would be less likely to be used in areas such as point of sale where high quality graphical reproduction is important, and the substrate/ink combination can be tailored to meet the color objectives. Given that print outcomes are dependent on both the ink and substrate (and its coating), an appropriate choice would need to be made regarding the trade-off between color obtained, volume of ink used and absorption/drying. The ink should not be absorbed so rapidly that a poor optical density is obtained, while excessively slow absorption can result in issues such as lateral spreading.

There are practical limitations imposed by the drying and absorption of the ink and immobilization of the pigment, especially when higher volumes of ink are deposited. To explore the full capabilities of the inks and inkjet head, the study used the maximum coverages possible (up to $\sim$ 60 gsm). However, it is not proposed that such high coverage is necessarily required for printed products. In this context, the benefits of higher-viscosity inks are probably best exploited at relatively low coverages (below 20 gsm) where there is a strong color contrast with respect to the standard-viscosity inks, yet coverage is not so excessive as to cause absorption or drying issues. There is a diminishing return in terms of increased color as gsm is increased, and the densities obtained in the 10 to 20 gsm range for high-viscosity inks are already substantially higher than for standard-viscosity inks (when the coated liner is used). At the highest coverage levels on coated liner, the higher-viscosity inks showed very high densities but also a mottling effect where the ink could not absorb readily into the substrate, and there was no real benefit in increasing coverage to this extent.

From a manufacturing perspective, the use of higher-viscosity inks provides the potential for productivity increases due to a smaller mass of ink being required for a given color, hence faster prints with fewer droplets or repeat depositions required to hit a target color. Further to this, the color gamut can be enlarged since the print density will not plateau as it would when using standard-viscosity inks (depending on the substrate). This potentially moves inkjet printing to a higher color intensity range, more associated with traditional analogue printing methods, while also offering benefits in terms of thicker layers for functional device printing (within the limitations of the substrate and drying/curing systems). Finally, the reduced mass of ink required, coupled with the higher solid content (and lower carrier content), requires lower amounts of solvent removal per printed area and hence a reduced energy expenditure with higher drying speed.

Conclusions

Conventional viscosity inkjet inks and higher-viscosity inkjet inks, not normally considered jettable, were printed on corrugated cardboard with both white coated and brown uncoated liners. Higher-viscosity inks were able to impart a greater color density to the print due to the inherently higher viscosity of the ink reducing penetration into the substrate as well as the higher pigment loading capable of being contained within the more viscous ink. While standard-viscosity inks tended to plateau in color intensity as coverage was increased, higher-viscosity inks could continually increase in color intensity on coated white liner. This effect was strongly dependent on the liquid absorption characteristics of the substrate, with a coated white liner of low absorbance exhibiting up to a 67% increase in maximum color density but uncoated brown liner of higher absorbance showing up to a 13% increase, with a flatter response to increased ink coverage. Given the diminishing return in terms of ink density increase with coverage and issues with absorption and drying, these benefits are best exploited at lower coverages.

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