Modern Colour Difference Equations and Their Relationship to Printed Ink Densities

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Abstract

The purpose of this research is to investigate the correlation of printed ink densities and numerical colour differences and to find out whether the ISO standard colorimetric requirements can be translated into a set of densitometric values. Can densitometers be used in press rooms as an effective tool for colour control? Does meeting the industry standards in terms of density values (i.e. GRACoL) yield to the colour conformance? How do paper characteristics such as surface structure, colour, brightness, etc. affect the reproduced colour? Also, which one of the colour difference equations should be used in the graphic arts industry? This paper attempts to answer these questions.

The results show that none of the five Delta E equations is dominant in terms of better correlation with density variations. If one choose to use the ΔE2000 which correlates better with the human eyes' perception of colour variations or DIN99 because of its more uniform colour space, different tolerances than those specified in ISO 12647-2:2004 must be used.

Within the group of coated stocks, the target densities achieved as the best colour match, are very close to each other, therefore it is possible to establish a target density and variation tolerance for each primary colour, in order to be used as a starting point to achieve a colour with the lowest ΔE as quickly as possible. However, different ink coverage is required to achieve that target density depending on the surface structure of the paper. Also, different sets of inks have different hue errors and grayness which should be considered by the printers.

Densitometers can be used effectively to control the density variations and therefore colour variations during a press run, but spectrophotometers are required – and becoming more crucial than before – to precisely control the conformance of the reproduced colours.

1. Introduction

Measuring and monitoring are the basis of standardization. Objective measurements of important printing properties such as the inking values of solids are crucial (Bestmann, 2006). Densitometers are a common tool in print shops to control the quality of the printed materials during the press run; but the density values tell the press operators nothing about the appearance of the printed colours. Many modern and larger printing facilities are equipped with spectrophotometers in order to control the colour variations. Researches have been done in attempt to translate the colour and density variations into each other. Seymour (2007) in his article "How Many ΔEs Are There in a ΔD?" shows that "densitometry and colorimetry are equivalent in terms of maintaining consistent colour on press". Also, "the colorimetric tolerances in ISO 12647-2 can be converted to a reasonable density tolerance" and "within a press run, running to a density tolerance will assure colorimetric tolerance". In addition, he converted the colour variation tolerances into density tolerances and concluded that "the conversion between densitometric and colorimetric tolerances for coated stocks is pretty much the same for all stocks" (Seymour, 2007, p. 333-334).

Table 1: CIELAB ΔE^*_{ab} tolerances for the solids of the process colours (ISO 12647-2:2004, p.7)

Parameters	**Colour**			
	Black	**Cyan** [a]	**Magenta** [a]	**Yellow** [a]
Deviation tolerance	5	5	5	5
Variation tolerance [a]	4	4	4	5

[a] The contribution of the hue difference shall not exceed 2.5.

In this paper, the deviation tolerances (table 1) are used to determine whether the reproduced colours conform to the ISO standards and to establish a target density for each colour that results in the lowest ΔE (if there is any). The question here is whether a press operator can use densitometry measurements and still meet the specified colour standards. Each paper has different surface structure, gloss, absorptivity and brightness. How do these characteristics affect the reproduced colour?

Since 1976, various colour differencing equations such as ΔE76, ΔE94, ΔEcmc and ΔE2000 have been established by colour scientists. The purpose has been to adjust the equations to more closely match with the human perception of colour differences (Habekost, 2007a, 2007b). In a research by Habekost (2007a, 2007b), it was established that the more recent equations (ΔE2000 and ΔEcmc) correlate well with the perceived differences by human eyes. Also, the latest tests on this topic revealed that ΔE2000 correlates better with the human perception of colour differences (Habekost M., personal communications, December 14, 2007). However, none of these formulas have a uniform colour space. DIN99 has been developed to address this issue. Also, this formula generally yields smaller values with better correspond to the visual impression ("DIN 6176"). But, which one of these equations does correlate better with density variations? Are the deviation tolerances the same for all the ΔE formulas?

2. Test Parameters

The custom mode of the Universal Testprinter (UTP) was set to the print length of 200 mm and speed of 1 m/s for print arm #1. A pre-measured amount of ink (using the Prufbau ink pipette) was applied to the rubber roller of the UTP inking unit and was distributed for 30 seconds. Then the printing disk was dropped on the rollers and inked up for another 30 seconds. The disk was then weighted on the digital balance. The analytical balance was connected to a computer with a data logging software installed on it. The printing disk was placed on the print arm #1 of the Testprinter and a print was made on the paper strip taped on the printing sector (printed area is measured 0.21m x 0.048m). The printing disk was again weighted. This procedure was repeated for the next 16 samples of the same paper without adding ink to the inking system, thus each printed sample had lower density (and ink film thickness) than the previous one.

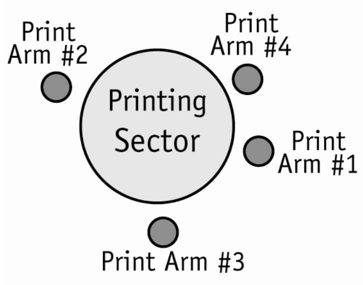

Figure 1: Diagram of the Universal Testprinter (courtesy of N. Kidd, Ryerson University)

The same procedure was followed for each process ink on each of four coated papers (16 sets of samples). It was allowed for at least 24 hours for the samples to dry before measuring them.

In the X-Rite Color Master QAII software, the spectral reflectance values of 0˚/45˚ geometry for each colour specified in ISO 2846-1:1997(E) were entered as the standard. Also, illuminant D50 and 2˚ observer were used as the standard settings. A spectrodensitometer connected to the computer was used to make three measurements on each sample. All the density measurements throughout the test were status T and made on white backing (3 sheets of unprinted paper).

The setting test was done on the Prufbau printability tester using 100 mm^3 of the setting test ink and pressure of 600 N. Also, the PSE test (Paper Surface Efficiency) was carried out using the K&N testing ink and averaged for both sides of the paper. The same spectrodensitometer was used throughout the test for all the parts.

The following equipment/materials were used for this research:

- Universal Testprinter printability tester and inking unit
- X-Rite spectrodensitometer, 500 series, X-Rite Inc.
- Prufbau ink pipette
- Denver Instrument analytical balance with Pinnacle USB version 1.2 software
- X-Rite Color Master QAII software
- Prufbau printability tester
- Novo-Gloss, Statistical Glossmeter, Rhopoint Instrument Ltd.
- Drawdown blade
- Setting Test Ink, 520068, Michael Huber Munchen GmbH
- K&N testing ink, NO. D79, K&N Laboratories Inc.

Table 2: Ink set used in this experiment

Hostmann-Steinberg, Huber Group		
Yellow	1 QK 1765	RAPIDA OPTIMA HiT PROCESS YELLOW
Magenta	2 QK 1765/5	RAPIDA OPTIMA HiT PROCESS MAGENTA
Cyan	3 QK 1765	RAPIDA OPTIMA HiT PROCESS CYAN
Black	8 QK 1765	RAPIDA OPTIMA HiT PROCESS BLACK

Table 3: Paper samples tested in this experiment

	Basis weight (lb.)	**Grammage (g/m^2)**	**Brightness**	**L***	**a***	**b***	**Gloss**
Phoenix APCO II/II (Standard paper)	100	160	84.72	96.15	0.09	4.13	72.20
Supreme Gloss Coated	80	120	90.55	94.71	0.88	-2.60	72.5
Exact Gloss Coated	70	100	90.24	94.11	1.70	-3.23	66.8
EuroArt Gloss	100	150	90.77	94.28	1.28	-3.49	75.2

3. Results and Discussion

3.1. Which Delta E Should Be Used: ΔE76, ΔE94, ΔEcmc, ΔE2000 or DIN99?

The question here is which one of the ΔE equations corresponds better to the density variations. To find out the answer, all 5 ΔE values of each colour on each paper were plotted as a function of density in a scatter diagram and the R^2 values of the 2nd order polynomial trendlines were determined. Also, the second set of diagrams was made by plotting the density values against the ΔE's of below and above target density in two separate diagrams (target density here is defined as the density yielded in the lowest ΔE). Out of 160 R^2 values for the second set of diagrams (5 ΔE's, 4 papers, 4 colours and below/above the target density), only three of them were lower than their relative values in the first set. Therefore, the later R^2 values have been used for the purpose of this section to determine which ΔE corresponds better to the density changes. Table 4 displays the ΔE equation that corresponded better to density variations for each process colour on all the papers (highest R^2s).

Table 4: The ΔE equation with the highest R^2 values for each colour

Yellow	**Magenta**		**Cyan**		**Black**
	Above target density	Below target density	Above target density	Below target density	
ΔE76	ΔE2000	DIN99	ΔEcmc	DIN99 and ΔE2000	DIN99

As the results show, only yellow and black samples have a dominant ΔE and can't determine a single ΔE equation that defines the best relationship between density and colour changes for all the colours.

Also, comparing the R^2 values in the first set of diagrams where all density values were plotted against ΔE's on the same diagram, only ΔE2000 was dominant for yellow and no single ΔE was found for the rest of the colours.

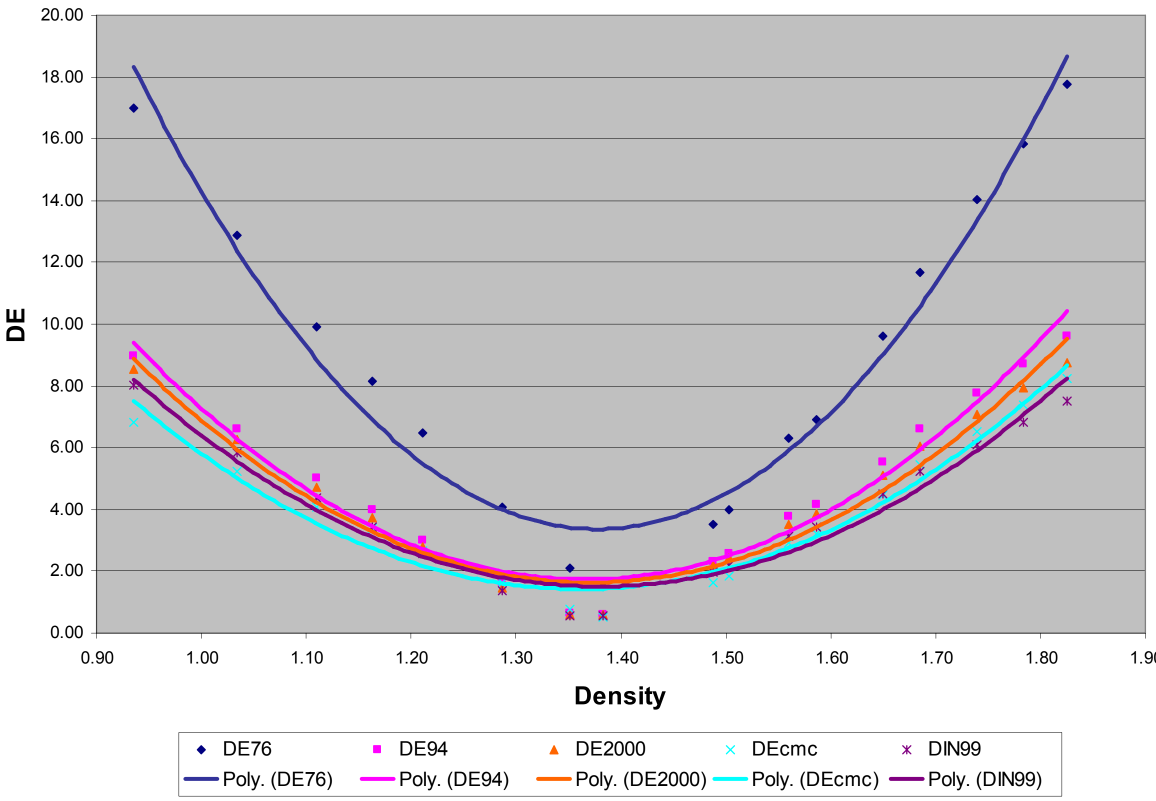

Figure 2: ΔE values versus density for magenta printed on Exact Gloss Coated

3.2. How Do L*a*b* Values Correspond to Density Changes?

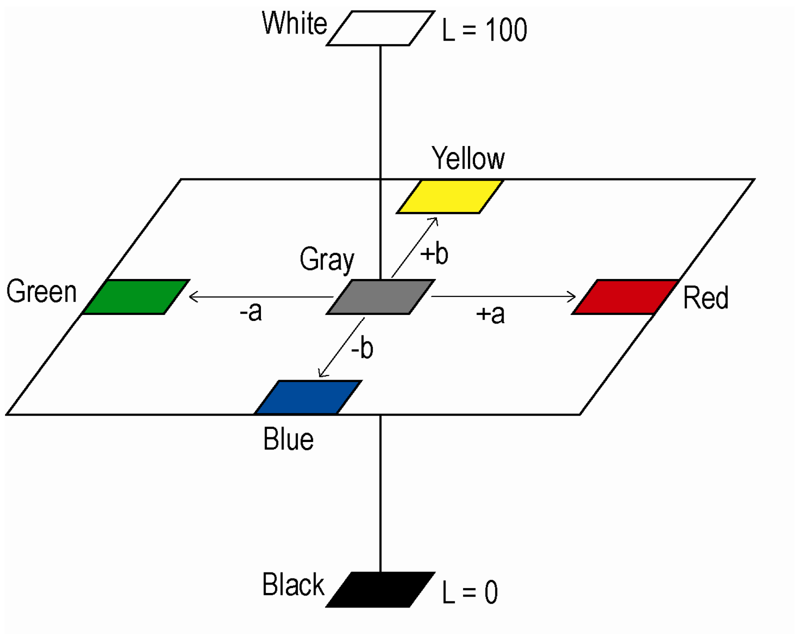

Figure 3: The CIE L a* b* colour scale (Based on Field, 1999)*

3.2.1. Density versus L*

For all four colours, as density increases, L* values decreases (colour becomes darker). The L* values are very close for all the papers printed with the same colour at any given density and in case of black samples, all four trendlines are on top of each other. The only exception is the Phoenix samples printed with yellow where they have higher L* values than other three papers. The unprinted Phoenix paper has higher lightness value than the other stocks. The L* value of the plain paper has a great influence on the L* value of the printed yellow than on the other process colours. Also, ΔL's are minimal from one sample to the next as density changes in yellow samples. Therefore the lightness of yellow remains almost the same as density increases.

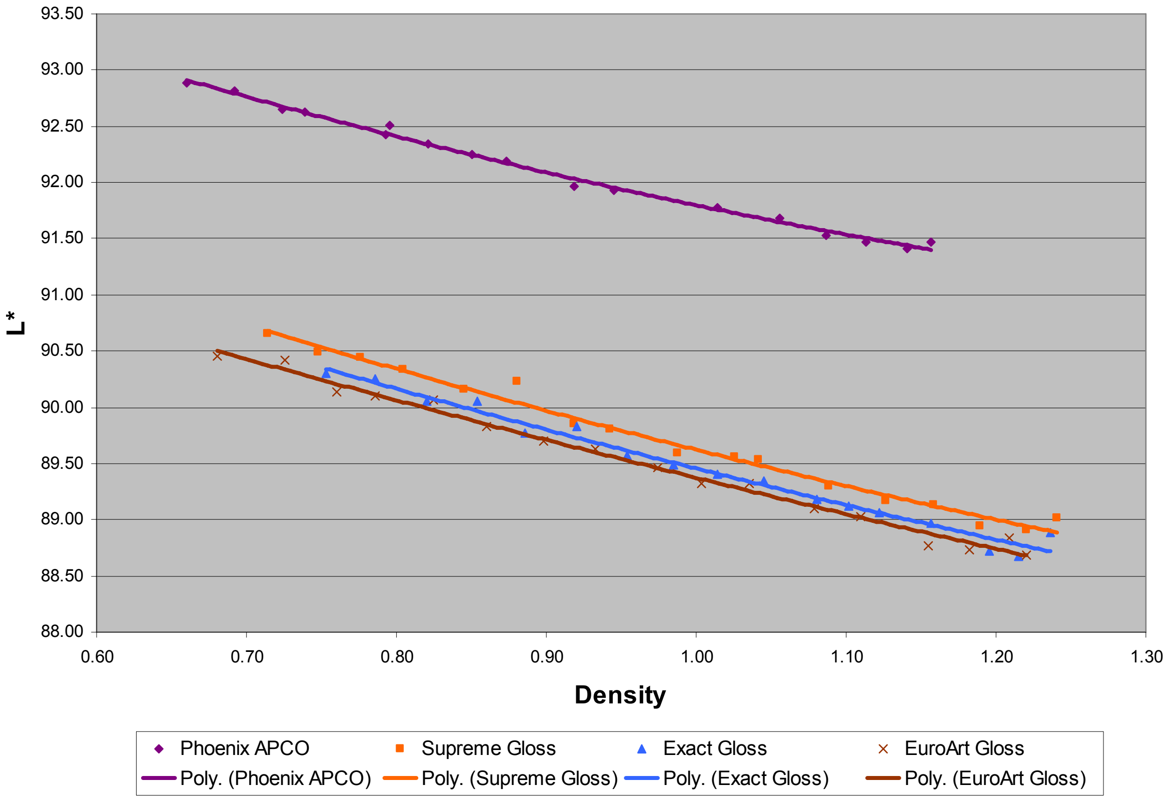

Figure 4: Density versus L for yellow printed on coated stocks*

3.2.2. Density versus a*

For yellow samples, Δa's are minimal for ΔD's below target density and they rise more quickly above the target density, whereas for magenta, Δa's are minimal for ΔD's above the target and the trendlines have a sharper upward slope below target density. Therefore, increasing the density of the printed yellow above target density causes the printed colour becomes slightly reddish as opposed to achieving a more saturated yellow.

Also, the trendlines for yellow and magenta tend to be linear compared to the parabolic trendlines of cyan and black. For cyan, a* is the lowest for the target density while for black, a* is the greatest at the target.

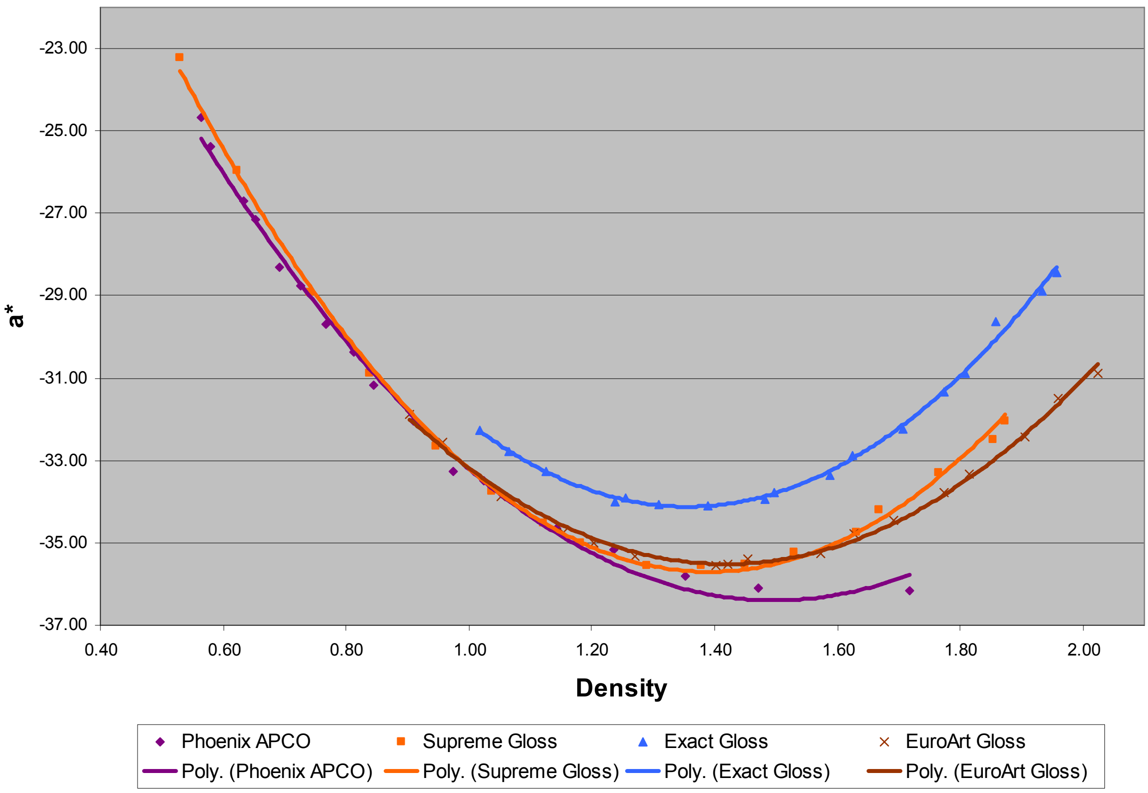

Figure 5: Density versus a for cyan printed on coated stocks*

3.2.3. Density versus b*

The Phoenix APCO samples have higher b* values than the other papers in all printed colours. The reason could be the fact that Phoenix is the only paper sample in this test which has a positive b* value (yellowish paper). For yellow and magenta, b* values increase as density increases (colour becomes more yellowish) while for cyan they decrease as density increases (colour becomes more bluish). For black all the trendlines with the exception of Phoenix paper are downward parabolic with the maximum point somewhere below the target density.

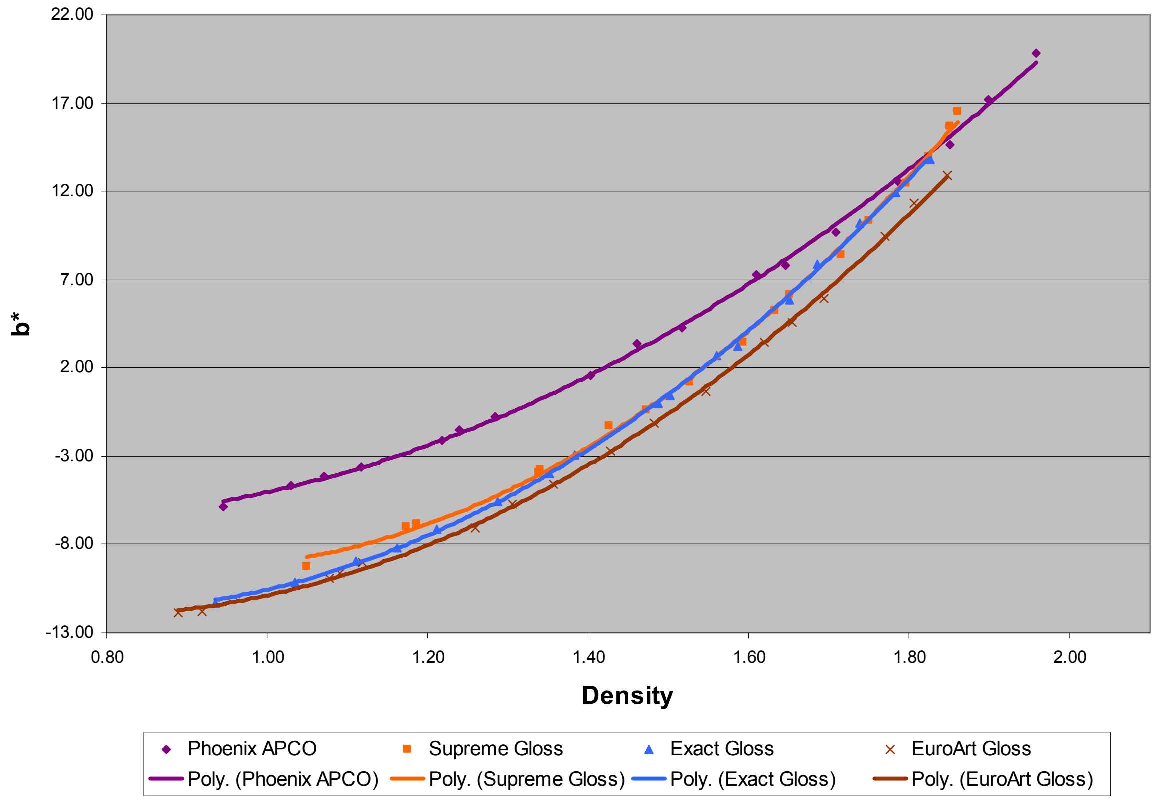

Figure 6: Density versus b for magenta printed on coated stocks*

3.2.4. Comparison of the Relationship between L*, a* and b* Values and Density of the Four Process Colours

Table 5 displays the slope of the L*a*b* values versus density (averaged for all papers). Note that for cyan and black, the slope is calculated for densities above and below the target in order to be comparable with the other non-parabolic trendlines.

Table 5: The slope of L, a* and b* versus density*

	Yellow	Magenta	Cyan	Black
Density vs. L*	-3.28	-13.06	-18.91	-27.19
Density vs. a*	5.13	13.73	8.38(above target) -10.65 (below target)	-1.40 (above target) 0.67 (below target)
Density vs. b*	67.16	27.94	-18.67	-5.51(above target) 1.27 (below target)

As the results show, black has the highest ΔL* and the lowest Δa* and Δb* slopes (the colour of black remains almost the same at various densities) (refer to figures 8 and 9). Also, yellow has the lowest ΔL* and the highest Δb* slopes. The Δa* slope is the greatest for magenta. Overall, comparing the a* and b* values of all colours as density varies, Δb* has the highest slope across all the colours. This means that as density changes, colours are more shifted between the yellow and blue corners of the colour space than between the red and green corners.

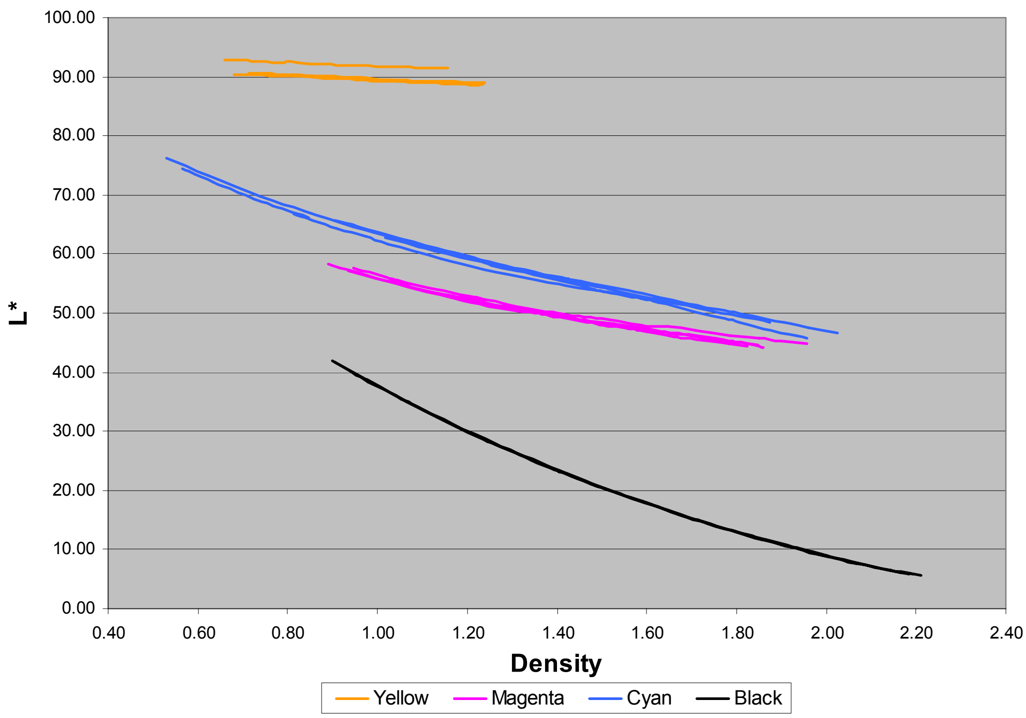

Figure 7: Density versus L for all the printed samples in this experiment*

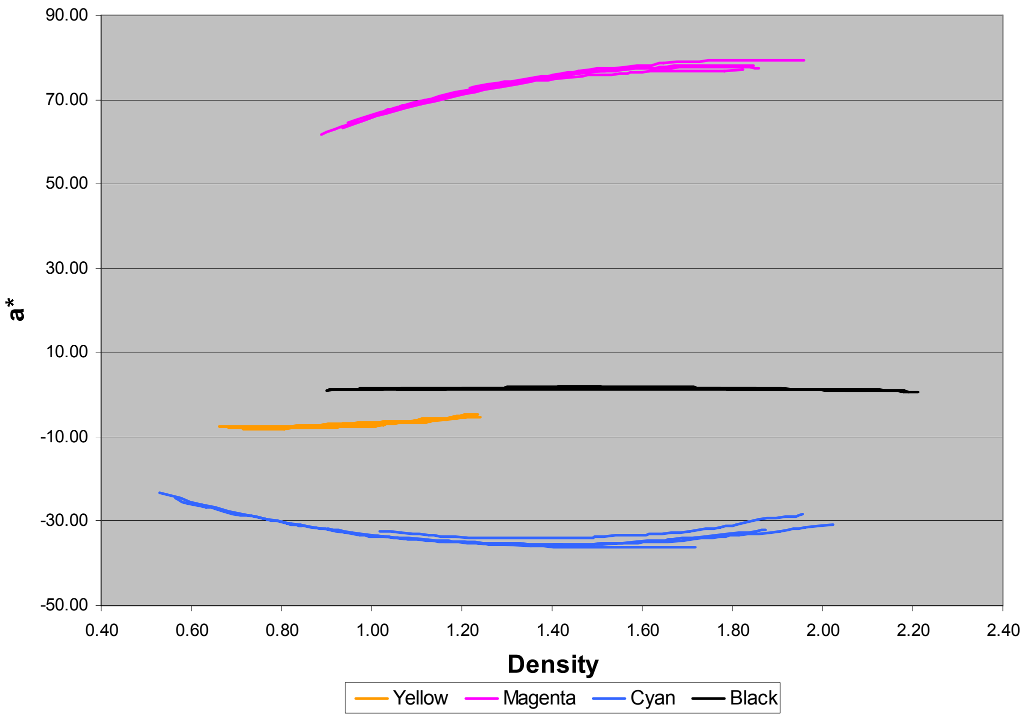

Figure 8: Density versus a for all the printed samples in this experiment*

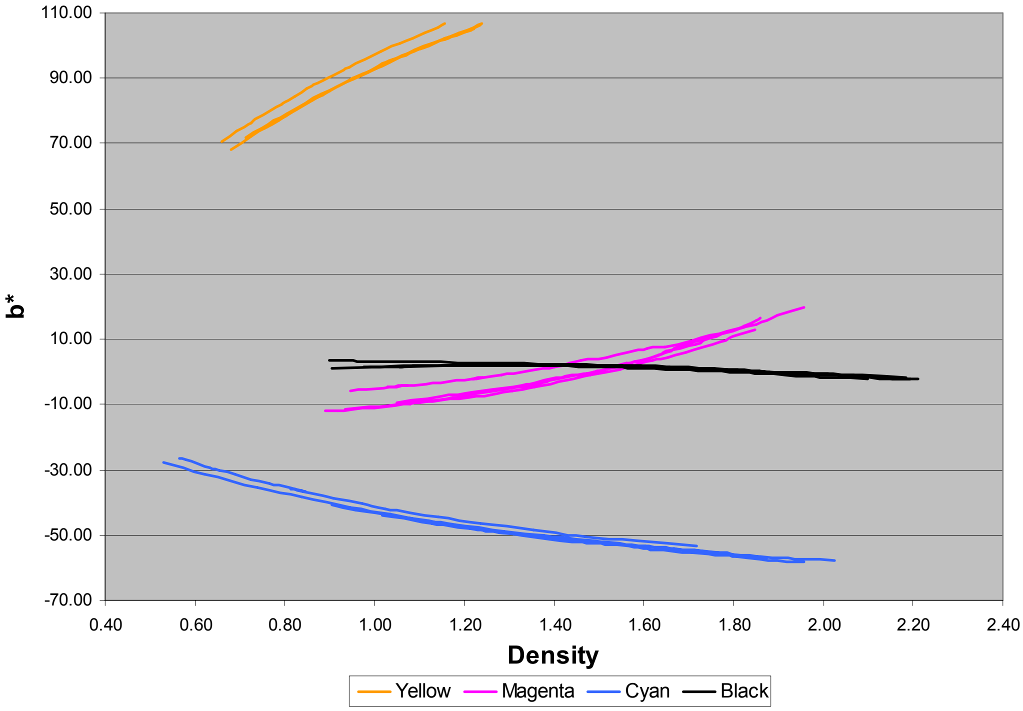

Figure 9: Density versus b for all the printed samples in this experiment*

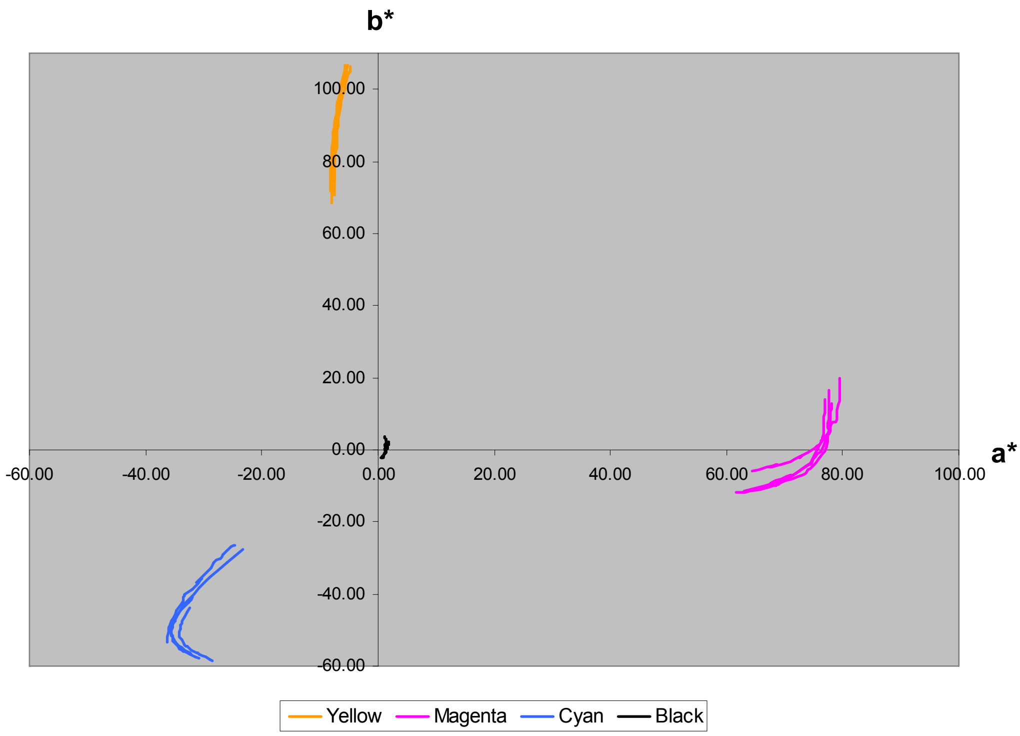

*Figure 10: Plot of a*b* values for all the printed samples in this experiment*

3.3. The Relationship between Density and ΔE76

The ΔE76 values of all samples were plotted as a function of density in a scatter diagram. In order to visually compare the effect of paper on ΔE as density changes, all ΔE values of papers printed with the same colour were plotted on the same diagram. The equation of each polynomial trendline was used to calculate the density values at which ΔE's are in the deviation tolerance (ΔE of 5) specified by ISO 12647-2 (refer to table 1 for deviation tolerances).

For example:

Yellow on Phoenix APCO: $y = 212.63x^2 - 415.87x + 207.97$
Y = ΔE76
X = Density
$Y = 5 \rightarrow X_1 = 1.02$ and $X_2 = 0.94$

$$\text{Mean (target density)} = \frac{X_1 + X_2}{2} = 0.98$$

$$\text{Tolerance} = \frac{X_1 - X_2}{2} = 0.04$$

Therefore for any density value between 0.94 and 1.02, the ΔE76 is equal or less than 5 which conforms to the ISO standards as an acceptable colour.

Table 6 and 7 show the density range for each paper and colour which yielded to ΔE76 equal or less than 5.

Table 6: Density range yielded to ΔE76 ≤ 5 for yellow and magenta samples

	Yellow			Magenta		
Paper	**Density range**	**Target density**	**Tolerance**	**Density range**	**Target density**	**Tolerance**
Phoenix APCO	0.94 – 1.02	0.98	±0.04	1.22 – 1.40	1.31	±0.09
Supreme Gloss	0.98 – 1.11	1.04	±0.06	1.21 – 1.55	1.38	±0.17
Exact Gloss	0.97 – 1.12	1.04	±0.08	1.23 – 1.52	1.38	±0.15
EuroArt Gloss	1.00 – 1.10	1.05	±0.05	1.22 – 1.56	1.39	±0.17
Average		**1.03**	**±0.06**		**1.36**	**±0.14**

Table 7: Density range yielded to ΔE76 ≤ 5 for cyan and black samples

	Cyan			Black		
Paper	**Density range**	**Target density**	**Tolerance**	**Density range**	**Target density**	**Tolerance**
Phoenix APCO	1.22 – 1.47	1.35	±0.13	1.50 – 1.84	1.67	±0.17
Supreme Gloss	–	1.29*	–	1.49 – 1.85	1.67	±0.18
Exact Gloss	–	1.24*	–	1.44 – 1.84	1.64	±0.20
EuroArt Gloss	–	1.27*	–	1.49 – 1.84	1.67	±0.18
Average		**1.29**	**±0.13****		**1.66**	**±0.18**

* For no X value, the trendline equation equals 5. The mentioned target density had the lowest ΔE76 among all the samples.
** The tolerance based on Phoenix samples only

Table 8: Target density comparison

	Yellow	Magenta	Cyan	Black
Achieved target densities in this experiment	1.03 ±0.06	1.36 ±0.14	1.29 ±0.13	1.66 ±0.18
Targets by Color Master software*	1.00	1.35	1.35	1.60
GRACoL targets	1.05	1.50	1.40	1.70
* These target densities are calculated by the Color Master software based on the typical spectral reflectance values, 0˚/45˚ geometry, ISO 2846-1:1997(E)				

Based on the results, black has the widest and yellow has the smallest density tolerance range. The cyan samples of the standard paper (Phoenix) were the only samples conforming to the ISO cyan colour. This paper does not have any optical brightener. The other three stocks are bluish white papers with optical brighteners. In order for cyan to be seen by human eyes, light is reflected from the blue and green areas and absorbed in the red area of the spectrum. Optical brighteners increase the light reflectance in the blue range of the colour spectrum. This artificial boost in the blue area where cyan has its highest reflectance values pushes the L*a*b* values out of ISO conformity.

The achieved target densities are close values in each set of samples printed with the same colour. These target densities are also close to the target densities calculated by the Color Master software based on the ISO reflectance values. However they are different from the GRACoL targets in case of magenta and cyan. This can be due to the fact that magenta and cyan have the highest hue error and grayness among the process colours (Breede, 1999). Therefore, it can be concluded that within the group of coated stocks, a target density can be established (based on colorimetric values) for a solid colour as long as the same ink is used. As a result, meeting the standard target densities (i.e. GRACoL) will not guarantee a colour match (lowest colour difference).

Table 9: Conversion of colour variation tolerances into density variation tolerances

	Yellow	Magenta	Cyan	Black
ΔE76/ΔD	59.57	36.08	24.89	25.54
ΔD/ΔE76	0.02	0.03	0.04	0.04
Density Variation Tolerances	±0.05 ((ΔD / ΔE76) x 2.5)	±0.06 ((ΔD / ΔE76) x 2)	±0.08 ((ΔD / ΔE76) x 2)	±0.08 ((ΔD / ΔE76) x 2)

According to ISO 12647-2:2004, "the colour differences between a production copy and the OK print shall not exceed, and should not exceed one half of the pertinent variation tolerances specified" (p. 6). Therefore, during the production, if the density variation tolerances in table 9 are met, the reproduced colours fall within the ISO colour variation tolerances (refer to table 1 for ISO variation tolerances).

3.4. Deviation Tolerances for ΔE2000

In the same procedure as in section 3.3 for ΔE76, ΔE2000 values were plotted against density and the related equation of each trendline was obtained. The density range that conforms to the ISO standard colour (calculated in section 3.3) was used to determine the ΔE2000 tolerance for each solid colour.

For example:

Yellow on Phoenix APCO: $y = 37.336x^2 - 75.642x + 39.572$
$Y = \Delta E2000$
$X = \text{Density}$
$X_1 = 1.02$ and $X_2 = 0.94 \rightarrow Y_1 = 1.26$ and $Y_2 = 1.46$

$$\text{Average} = \frac{Y_1 + Y_2}{2} = 1.36$$

Therefore, if the colour difference of yellow printed on Phoenix paper calculated using ΔE2000 equation is equal or less than 1.36, the colour conforms to the ISO standard yellow.

Table 10: ΔE2000 deviation tolerances for solids of the process colours

	Yellow	Magenta	Cyan	Black
Phoenix APCO	1.36	2.75	2.83	3.57
Supreme Gloss	1.63	2.55	3.03	3.72
Exact Gloss	1.57	2.45	3.41	3.74
EuroArt Gloss	1.66	2.55	3.23	3.69
Average	**1.56**	**2.57**	**3.13**	**3.68**
Suggested ΔE2000 Deviation Tolerance	**1.60**	**2.60**	**3.20**	**3.70**

Table 10 shows the deviation tolerances for ΔE2000 within which the colour conforms to the ISO standard colours. These deviation tolerances for ΔE2000 equation are lower than those specified in ISO 12647-2:2004 for ΔE76. Therefore, if different ΔE formula is selected for colour control purposes, new deviation tolerances need to be established. Table 10 also displays the suggested ΔE2000 tolerances.

3.5. Deviation Tolerances for DIN99

In the same way as in section 3.4 for ΔE2000, the deviation tolerances were calculated for DIN99. Table 11 displays the deviation tolerances for DIN99 within which the colour conforms to the ISO standard colours.

Table 11: DIN99 deviation tolerances for solids of the process colours

	Yellow	Magenta	Cyan	Black
Phoenix APCO	1.28	2.52	2.66	6.27
Supreme Gloss	1.59	2.31	2.88	6.14
Exact Gloss	1.58	2.22	3.32	6.27
EuroArt Gloss	1.65	2.31	3.12	6.22
Average	**1.52**	**2.34**	**3.00**	**6.22**
Suggested DIN99 Deviation Tolerances	**1.60**	**2.40**	**3.00**	**6.30**

3.6. The Relationship between Density and ΔE76, ΔE2000 and DIN99

The plot of ΔE values versus density for each paper printed with each one of the process colours shows that ΔE2000 and DIN99 have a very close values in yellow samples and as the colour gets darker (comparing the lightness of the four process colours in order of yellow, cyan, magenta and black) the difference between ΔE2000 and DIN99 values becomes larger (figure 7 shows the difference between the lightness of four process colours). Also, ΔE76 has the highest colour difference values and the highest slope (ΔE/ΔD) among all the ΔE equations for yellow, magenta and cyan samples. However, for black samples, DIN99 has the greatest colour difference values as well as the highest slope (ΔE/ΔD).

As demonstrated in section 3.3 and table 9, colour variation tolerances defined in ISO 12647-2:2004 can be translated into a set of density variation tolerances. Table 12 displays suggested density variation tolerances for ΔE2000 and DIN99 equations. The colour variation tolerances for ΔE2000 and DIN99 were assumed to be the same as their deviation tolerances. Therefore, if the density variation tolerances are met during production run, the reproduced colours will fall within the colour variation tolerances as the acceptable colour.

Table 12: Comparison of the relationship between density and ΔE76, ΔE2000 and DIN99 and the suggested density variation tolerances for ΔE76, ΔE2000 and DIN99

		Yellow	Magenta	Cyan	Black
ΔE/ΔD	**ΔE76/ΔD**	59.57	36.08	24.89	25.54
	ΔE2000/ΔD	10.29	18.16	16.20	17.15
	DIN99/ΔD	9.76	16.27	15.72	32.57
ΔD/ΔE	**ΔD/ΔE76**	0.02	0.03	0.04	0.04
	ΔD/ΔE2000	0.10	0.06	0.06	0.06
	ΔD/DIN99	0.10	0.06	0.06	0.03
Density variation tolerances: (ΔD/ΔE) x (1/2 colour variation tolerance)					
ΔE76		±0.05	±0.06	±0.08	±0.08
ΔE2000		±0.08	±0.08	±0.10	±0.11
DIN99		±0.08	±0.07	±0.09	±0.10

3.7. Ink Coverage

The ink coverage and the ink film thickness of each printed sample were calculated using formulas specified in ISO 2834:1999(E) (formula 1 and 2).

Ink coverage:

$$C = \frac{m_1 - m_2}{A} \qquad (1)$$

C = Ink coverage (in grams per square meter)
m_1 = The mass of the ink forme before printing (in grams)
m_2 = The mass of the forme after printing (in grams)
A = The printed area (in square meter)

Ink film thickness:

$$d = \frac{C}{\rho} \qquad (2)$$

d = The ink layer thickness (in micron)
C = The ink coverage (in grams per square meter)
ρ = The mass density of the ink (refer to table 13)

Table 13: The mass density of the inks used in this experiment

Hostmann-Steinberg, Huber Group			**Mass density (g/cm^3)**
Yellow	1 QK 1765	RAPIDA OPTIMA HiT PROCESS YELLOW	1.0487
Magenta	2 QK 1765/5	RAPIDA OPTIMA HiT PROCESS MAGENTA	1.0958
Cyan	3 QK 1765	RAPIDA OPTIMA HiT PROCESS CYAN	1.0483
Black	8 QK 1765	RAPIDA OPTIMA HiT PROCESS BLACK	1.1143

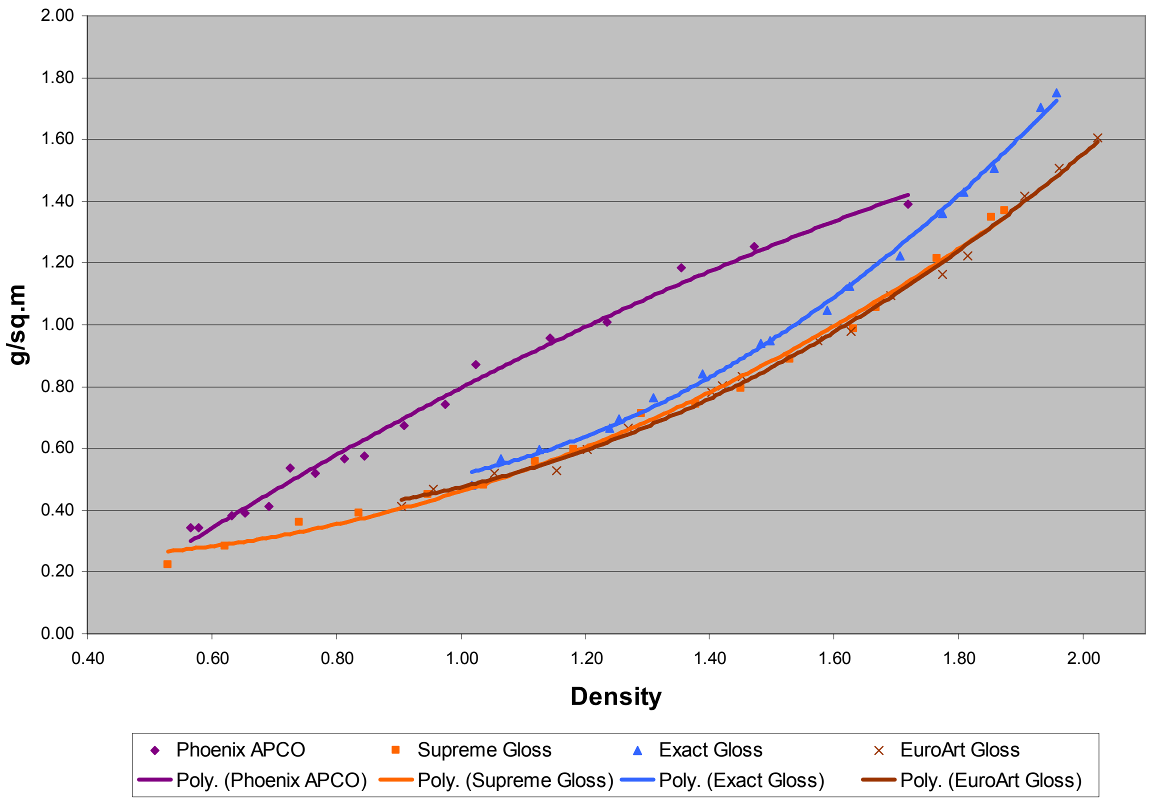

Figure 11: Ink coverage as a function of density for cyan printed on coated stocks

As figure 11 shows, the Phoenix paper has the highest ink coverage at the target density (1.29). This means that more ink is required to achieve the target density on Phoenix paper than on the other stocks. The results were the same for all four colours. The first assumption as the reason of the difference between Phoenix and the other stocks was the higher absorptivity of the Phoenix paper. In order to verify the assumption, the PSE (paper surface efficiency) test was done on the papers.

Paper Surface Efficiency: $$\text{PSE} = \frac{(100 - A) + G}{2} \qquad (3)$$

A = Absorptivity of paper (in %)
G = Gloss of paper (in %)

Table 14: PSE results for the tested coated papers

	Phoenix APCO	Supreme Gloss	Exact Gloss	EuroArt Gloss
Absorptivity	17.16	19.8	19.8	17.16
Gloss	72.20	72.5	66.8	75.2
PSE	77.52	76.35	73.5	79.02

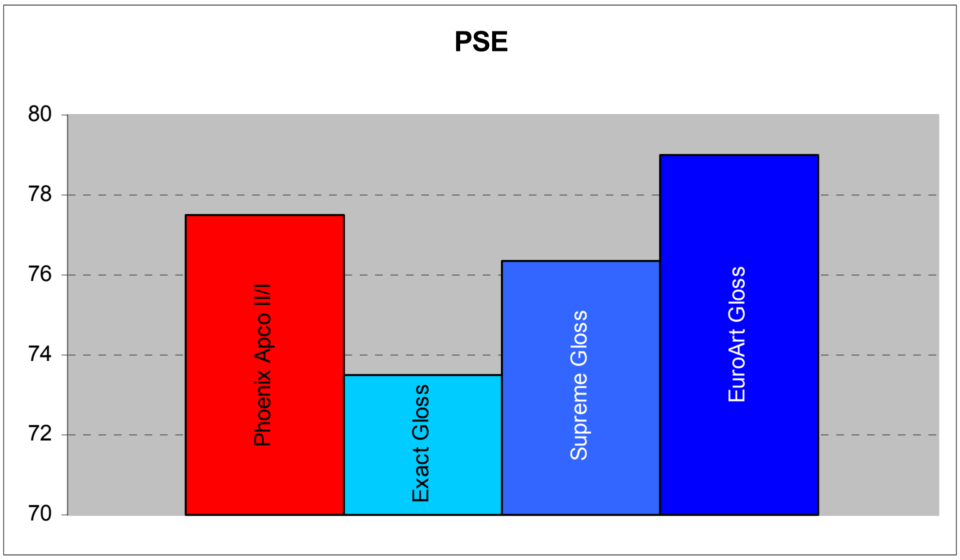

Figure 12: PSE results for the tested coated papers

For further determination of the paper/ink relationship, the ink setting test was carried out on the Prufbau printability tester. The setting test ink from Michael Huber Munchen (Germany) was used for this test. The density of the solid ink film and the first transferred stain onto the unprinted paper were measured (Table 15). The higher the density of the transferred stain, the lower the amount of ink is that has been set into the paper.

Table 15: Setting test results

	Density of the printed ink film	Density of the 1st transferred stain onto the unprinted paper
Phoenix APCO	0.90	0.35
Supreme Gloss	1.05	0.39
Exact Gloss	1.02	0.24
EuroArt Gloss	1.05	0.44

Based on the results, Phoenix is a fast-setting paper which had the lowest initial density and the second lowest ink transfer to the unprinted sheet in the setting test. On the other hand, EuroArt Gloss had the best ink holdout. The absorptivity values from the PSE test did not match the setting test results. In order to find out which test is more reliable, the microscopic images of the paper surfaces were taken by AFM (Atomic Force Microscope). Figure 13 is the 3D model of the AFM images:

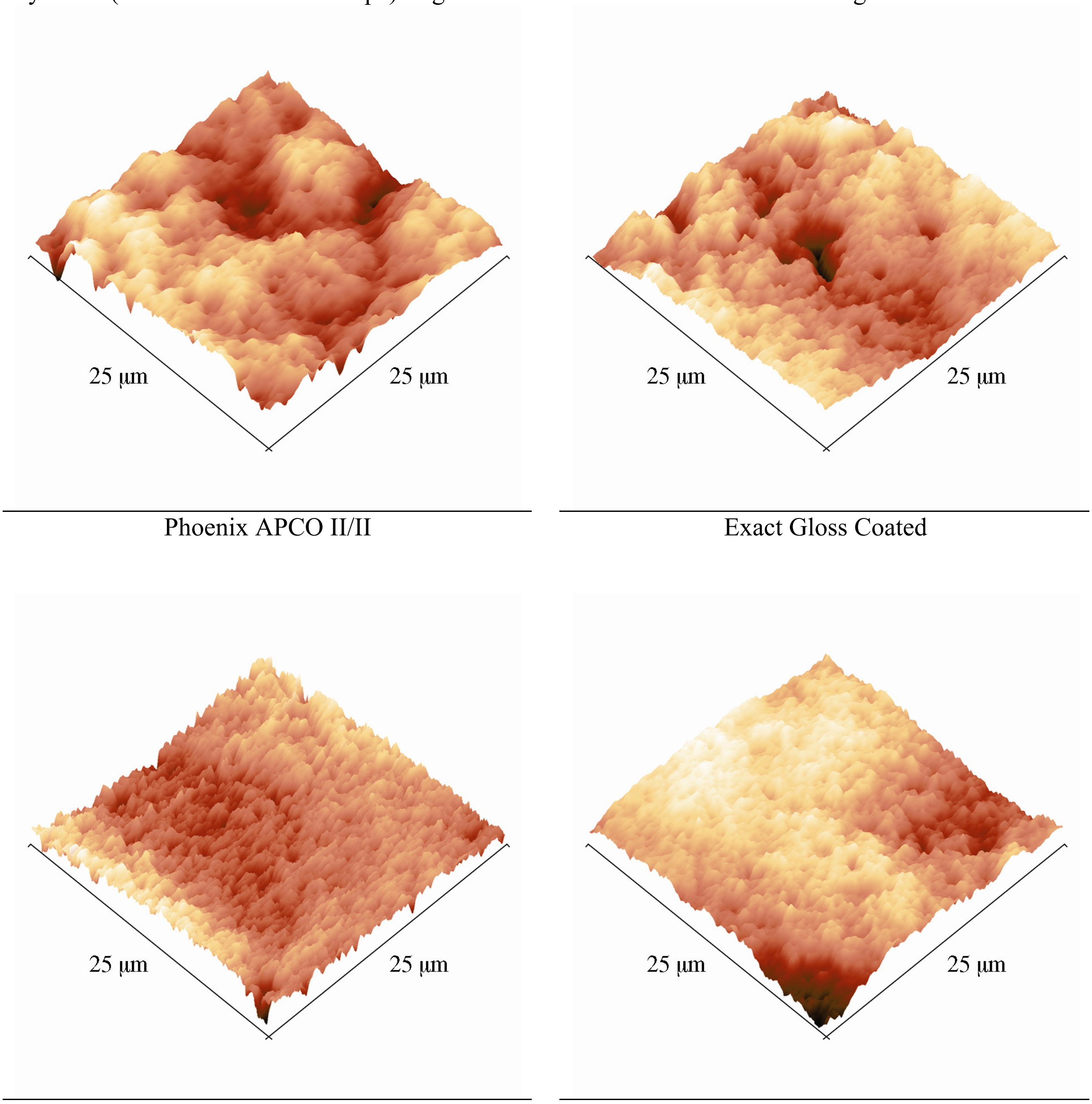

Figure 13: The AFM pictures of the surface of the tested papers

The AFM images clearly show the evenness of each paper surface. It is clear by images that the Phoenix paper has the most irregular surface among all the papers tested in this experiment. Therefore it needs more ink to fill up the voids of the surface and reach the target density while other papers with more even surface have better ink holdout and need less ink coverage. As a result, the setting test results are a better prediction of the surface behaviour than the PSE tests. Yet, none of these tests consider the colour of the paper and therefore not reliable in terms of predicting the colour of the printed ink film.

4. Conclusion

Seymour (2007) established that densitometry and colorimetry are equivalent in terms of maintaining consistent colour on press and provided ΔD tolerances for each ΔE (ΔE76) variation tolerances specified in ISO 12647-2:2004. I would add that a target density can be established for each colour within the group of coated stocks as long as the same ink is used due to the inherent hue error and grayness of inks.

Establishing the GRACoL densities can be a starting point to adjust the ink zones and get close to the optimum colour, but colorimetry is necessary to obtain the OK sheet. During a press run, a densitometer can be used to control the density variations while meeting the colour variation tolerances. Depending on the brightness level of paper, cyan is the only colour for which a press operator may not be able to achieve a ΔE76 less than 5.

As density increases/decreases, the largest change in colour of printed ink happen with b* values than with a* (colour is more shifted between the yellow and blue corner of the colour space than between red and green). Black has the lowest a* and b* changes and highest L* changes as density varies while yellow has the lowest L* and the highest b* changes. The greatest a* change rate belongs to magenta.

None of the five ΔE equations has a better correlation with density than the other ones. If one chooses to use the ΔE2000 equation for the purpose of colour control (because of its better correlation with the human eyes' perception of colour differences), or DIN99 (due to its uniform colour space), the following deviation tolerances are suggested (table 16):

Table 16: Suggested colour deviation tolerances for ΔE2000 and DIN99 equations

	Yellow	**Magenta**	**Cyan**	**Black**
ΔE2000	1.60	2.60	3.20	3.70
DIN99	1.60	2.40	3.00	6.30

The ISO 12647-2:2004 colour variation tolerances as well as the suggested colour deviation tolerances (table 16) (which are assumed to be the same as variation tolerances in this experiment) can be translated into a set of density variation tolerances for each colour difference formula (table 17). If these density variations are met during production run, the reproduced colour will conform to the ISO standard colours.

Table 17: Suggested density variation tolerances for ΔE76, ΔE2000 and DIN99 equations

Density variation tolerances: (ΔD/ΔE) x (1/2 colour variation tolerance)				
ΔE76	±0.05	±0.06	±0.08	±0.08
ΔE2000	±0.08	±0.08	±0.10	±0.11
DIN99	±0.08	±0.07	±0.09	±0.10

Depending on the evenness of the paper surface, different amount of ink – and therefore different ink coverage (g/m^2) and ink film thicknesses – is required to achieve the target density. The more even the surface of the paper, the lower the amount of ink needed to achieve the optimum colour.

The setting test results are a better prediction of the effect of the paper surface structure on the ink coverage than the PSE test. However, none of these tests predict the colour of the paper and its effect on the reproduced colours.

5. Future Research

The test samples have been printed on the Universal Testprinter which cannot simulate some of the actual processes happening during a press run. For example ink-water balance is an important factor affecting the appearance of colour. In a future research, the laboratory results will be verified in a local printing facility. In addition, this test was done only on coated stocks. The same test will be carried out on uncoated stocks and the results will be compared.

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