QUANTITATIVE ANALYSIS OF PRINTING VARIABLES AFFECTING SHADES IN SCREEN-PRINTED TILES

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The present study undertakes to evaluate how and to which extent a series of quantitatively measurable production parameters affect variations in mean colour (shades) of decorated tiles. In industrial production the screen-printing system gives rise to shades in tiles, which directly affect costs and yield [AMO 92].

Other authors have shown that raising ceramic production quality can produce considerable savings [COR 96].

Shades make sorting necessary at the end of the production line. They also entail storage costs as a result of classification, as well as costs relating to sorting facilities. Taking into account the costs and complexity of the production process involved, a series of experiments was programmed, based on a balanced design, as recommended by some authors [CORb 96].

Certain studies have shown the way in this field, such as the work by Corma and other investigators [COR 96, PEÑ 96], and these have served as a starting point for this study.

1. OBJECTIVES

The appearance of shades was studied by considering *screen tension, off-contact, ink viscosity* and *squeegee angle*. A balanced analysis was defined with these variables, using at least three levels in studying each.

The intention was to obtain balanced designs with a series of points enabling us to:

A) Confirm the existence of a relation between the variable and colour (by preliminary variance analysis), and subsequently, on having verified the existence of a relation between the variables:

B) Study a possible regression model.

2. MATERIAL AND METHODS

2.1. EXPERIMENTS CARRIED OUT

2.1.1. EFFECT OF TENSION, OFF-CONTACT AND VISCOSITY

Four tiles were printed for each combination of parameters. The first two were systematically discarded and the second two retained. The squeegee chosen for the trials was sharpened beforehand. Squeegee pressure was not measured, always using the minimum squeegee pressure required to obtain the print. Printing speed was held steady. All the specimens were printed at the same temperature without using a compensator. Tests were run with a Nasseti, Model Serimeck TOP 101, printing head. On obtaining the series of tiles, they were fired together to avoid the possibility of shades arising as a result of the kiln.

Image design was performed by the Error Diffusion pattern [FLO 75] and a patented methodology [PER 75].

The tests conducted were the result of crossing all the possibilities of the following combinations:

- Screen tension. Three screen tension values. Tension was measured with a tensometer having a sensitivity of 0.1 N/cm. Tension was measured in the two directions parallel to the frame edge; in all cases the differences were less than 0.5 N/cm between both directions. Printing screens were prepared in every case 48 h prior to testing. The following three tensions were studied: 16, 20 and 25 N/cm.

- Off-contact. Off-contact was measured at the four ends of the screen using a graduated wedge. Two series were measured, four at the same level in the four corners and six as a result of combining a different *off-contact* between the start and end of the squeegee stroke, in accordance with its direction. The lower value was always taken at the end of the printing run. The data were measured in mm. These were as follows: a) At the same level: 4, 5, 7 and 9 mm; b) With differences between start and end of the squeegee printing travel: 4-6, 4-8, 4-9, 6-8, 6-10 and 8-10 mm.

- Viscosity. Viscosity was measured with a Ford Cup (DIN 53.211), consisting of a cup with a given capacity, which has a funnel-shaped end with an opening at the bottom. Viscosity values were measured at 20 °C. The time required to empty the cup served to indicate ink viscosity. The values analysed in testing were 1.5, 2.5 and 3 minutes.

2.1.2. EFFECT OF SQUEEGEE ANGLE

Objective: The aim was to determine the optimum working squeegee angle, and establish whether this optimum was affected by wear or not.

A balanced test was designed, involving the series resulting from a combination of the following parameters.

- Squeegee angle. The angle was measured on both sides of the squeegee with the aid of a protractor. The protractor was put on the screen, and the angle read that the squeegee rim formed with the screen on the printing surface. The angles were measured in sixtieths of a degree and corresponded to the following values: 30, 40, 50, 60, 70 and 80 degrees.

- Two squeegees made of the same material were chosen, of which one had been used during a day's production, while the other had been recently sharpened. The data were referenced A (sharp squeegee) and G (worn squeegee).

2.1.3. EFFECT OF VISCOSITY

Objective: Defining the variation in colour in terms of viscosity.

Using the analysed parameters of the two foregoing tests, an experiment was defined in which viscosity was varied by keeping squeegee angle (60 deg.), screen tension (25N/cm), and off-contact (5 mm) constant. A total of 6 specimens was developed.

2.2. RESULTS

Of the 90 specimens corresponding to the possible combinations of the above data (Section 2.1.1.), a total of 85 specimens was obtained, 5 being lost by breaking.

In the second specific angle experiment (Section 2.1.2.) the 12 targeted specimens were obtained in experiment.

In the third series relative to ink viscosity (Section 2.1.3.) the 6 targeted specimens were obtained in experiment.

Colour data were obtained with a Minolta, Model CR300, colorimeter, using the

CIELAB or CIE 1976 L* a* b* readings, where L represents luminosity (varying from zero (black) to 100 (white)), a represents green (negative) and red (positive), and b represents blue (negative) and yellow (positive). As the ink was black, the value considered in all the experiments was the value of L[1].

This value was read at 8 different points on each tile, two in each corner, corresponding to two levels of grey printed in the four corners of the tile.

3. RESULTS AND DISCUSSION

3.1. GENERAL STUDY

Study by variance analysis of the main factors affecting shades in tiles.

Variance analysis for MEDO - Sum of squares					
Origin	Sum of squares	Df	Sq. Mean	F-Ratio	P-Value
PRINCIPAL EFFECTS					
A:FCA	58,6413	5	11,7283	6,49	, 0
B:TINT	46,0469	2	23,0234	12,75	, 0
C:TP	15,4942	2	7,7471	4,29	, 172
RESIDUE	135,465	75	1,8062		
TOTAL (CORRECTED)	260,286	84			
Aall the F-ratios are bases on the residual square mean error					

Table 1. *Variance analysis. Effect on the %variations in mean colour of the tiles owing to off-contact, ink viscosity and screen tension. It can be observed on analysing these three factors together, that the variations found in the experiments as a result of these factors were statistically significant.*

Variance analysis indicated the parameters affecting specimen mean colour (this variable was referenced MEDO). The parameters whose P value was lower than 0.05 were considered significant.

The data set out in table 1 allow inferring that the variation in the value of L represented by the MEDO variable was amongst other factors influenced by ink viscosity, screen tension and "*off-contact*". These variation factors were statistically significant.

Changing screens can modify at least three factors *First* the new screen may have a different tension, *secondly* on positioning the screen off-contact may be altered, and *thirdly* squeegee printing pressure may change. Changing screens is unlikely to affect viscosity. Other variation factors that were not studied in the model involved those of the screen preparation process, such as the variation in emulsion thickness or exposure. These variables were kept steady in our experiments.

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[1]. There is no standard on comparing colours in different studies. The most widespread method is perhaps the study of DE. A series was tested using ΔE and L, however the differences in the outcomes were nil so that it was decided to simplify and only take the L value

Plotting the variables defined in the above model allowed estimating the possible linear correlation between shades and printing parameters.

On plotting the data of the mean L value versus "off-contact" and tension by identifying different viscosity points, it can be observed that the scatter in shades was less at high viscosity than at low viscosity.

This justified performing multivariate regression analysis to determine how shades changed with high viscosity.

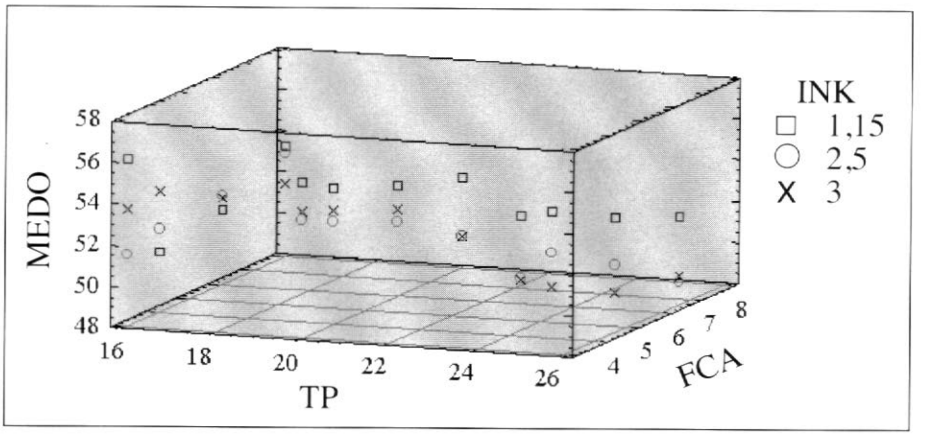

Figure 1. *Mean value of the MEDO variable (Mean L value of the specimens) as a function of screen tension (TP) and off-contact (FCA). The values shown indicate ink viscosity.*

Integrating the value of *"off-contact"* together with screen tension in a single equation allows analysing the effect of both variables in a single model.

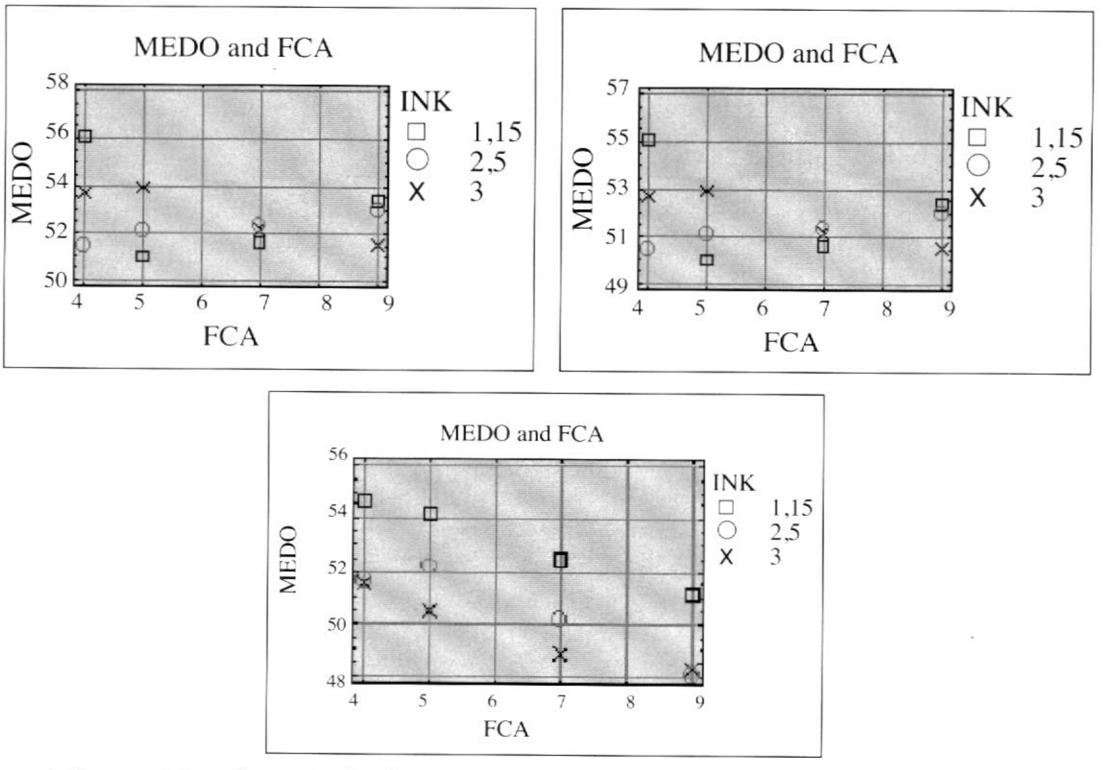

Figure 2. *Representation of mean L value for a screen tension of 16N/cm (top left), 20 N/cm (top right) and 25 N/cm (bottom). It can be observed that at a viscosity of 1.5 min the tendency inverted for the screen tensions.*

In the above graphs of Figures 2 and 3 the differences as a result of viscosity were of the same order in almost every case, but became larger at higher tensions. Their influence on shades was much less than that of *"off-contact"*. However, at tensions exceeding 16N/cm, the differences were of the same order.

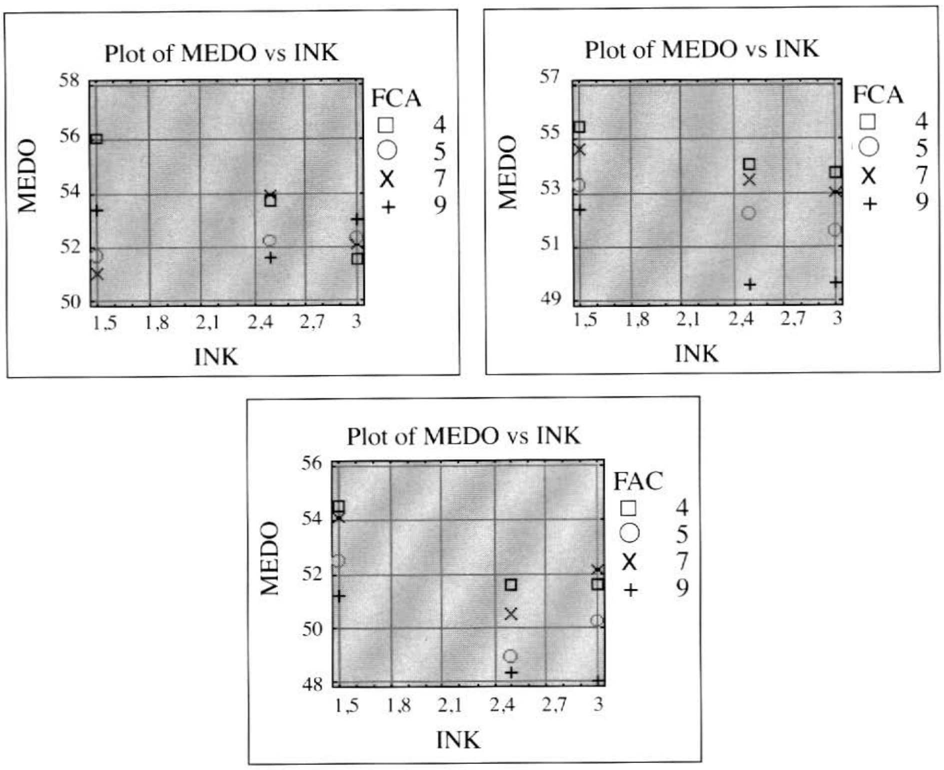

***Figure** 3. Representation of mean L value in terms of the three ink viscosity values studied, plotted for a screen tension of 16N/cm (top left), 20 N/cm (top right) and 25 N/cm (bottom). It can be observed how differences arose amongst the groupings for each ink and tension, which show a slight trend.*

On considering the above, it was decided to study the quantitative relations between mean L value and the other parameters. A study was undertaken of how each parameter affected the value of L (MEDO variable), subsequently attempting to establish a general regression equation with all the parameters.

A study was made of shades in terms of *"off-contact"* by regression analysis. The arising variation in colour (shades) was studied keeping constant screen tension and ink viscosity, which yielded a regression straight line with an R squared of 96.4% (i.e. under experiment conditions the model covers over 90% of the variability). (Table 2 and Figure 4).

The equation's coefficient was –0.88, indicating that the larger the *"off-contact"*, the lower the value of L, i.e., the closer it was to black. Ink release or the resulting print yielded a darker image with larger off-contacts.

Increased off-contact produced lower L values in the print, which meant a darker image. This could be due to two factors, either that more ink was deposited or that the ink spread. These data match other findings [COU 96], which indicate that at a larger off-contact dot size grows and the image darkens, hence producing a possible loss in colour range.

The data match the theory put forward by other authors suggesting a reduction in *"off-contact"* to achieve a better quality print [PEYb 89]. The *"off-contact"* factor depends on screen tension; a tension that is too low impedes using an *"off-contact"* that is very small, a high tension entails using lower contact forces in order to reduce screen stresses.

The effect of *"off-contact"* on specimen mean shade was appreciable. According to the data in table 2, each mm increase in "off-contact" (FCA) produced -0,85% variation in colour relative to the total, which corresponded to a value of 0.81 for L (CIE). In other words, a difference of 5.9 mm in off-contact entails a change of 5 points in the value of L with a probability of 96.4% (provided experiment conditions are held, with screen tension of 20 N/cm, and viscosity of 2.5 minutes).

```
Correlation Coefficient = -0.981592
R-squared = 96.3522 percent
Standard error = 0..467142
```

MEDO = 57.8479 - 0.884068*FCA

Table 2. *Linear regression model between MEDO and FCA. The linear regression model fits with R-squared at 96 %, and exhibits a statistically significant index. The study was carried out for variable "off-contacts", though equal in the four corners, a screen tension of 20N/cm and an ink viscosity of 2.5 minutes.*

The MEDO value is a measure of total colour differences or shades. The variations produced by *"off-contact"* may reach 50% of total variations.

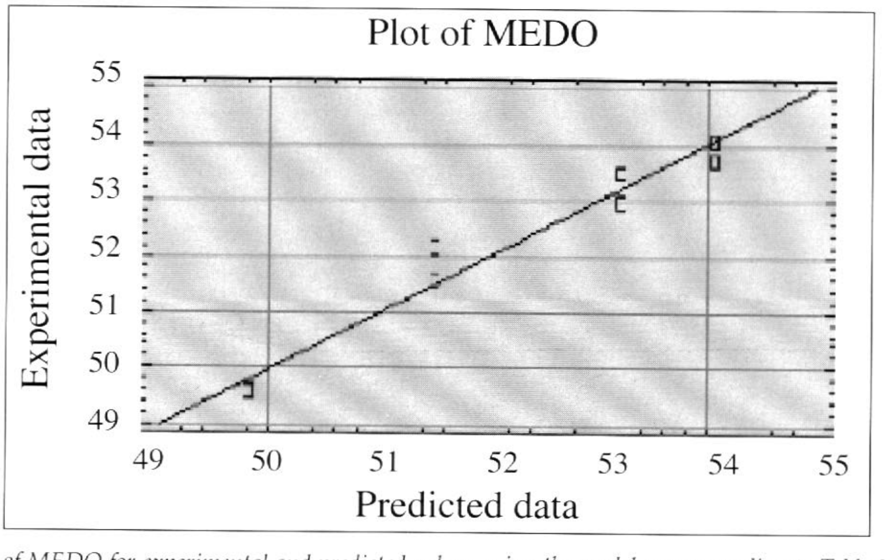

Figure 4. *Plot of MEDO for experimental and predicted values using the model, corresponding to Table 2, between the mean L value for the grey reference value found for each specimen and "off-contact" in mm. The data were obtained at a constant viscosity and screen tension. On raising "off-contact", L dropped and the specimen became a darker shade.*

As already mentioned, changes in *"off-contact"* do not usually occur independently; they tend to be the result of a series of interrelations with other parameters. Variations in *"off-contact"* are usually associated with two other factors: squeegee hardness and screen tension.

A very soft squeegee requires either applying greater squeegee pressure or reducing *"off-contact"*. Lower screen tension usually requires lifting the screen and raising *"off-contact"*.

With regard to the specific problem addressed in the experiment for a given screen tension and a given squeegee, a change in *off-contact* produced changes in colour, which fitted a linear regression straight line. The change in *off-contact* occurred simultaneously on readjusting squeegee pressure.

A rise in squeegee pressure produces a larger contact area between the screen and the tile, which explains darkening of the image as a result of ink spread. On the other hand, this rise produces a lower squeegee contact angle with the fabric. Testing was conducted at a constant 60-deg. angle. As will be discussed below, at the angles used in the study the relation between angle and shade was linear and positive, which meant that a smaller angle modified the value of L in a falling direction, i.e., towards darker shades.

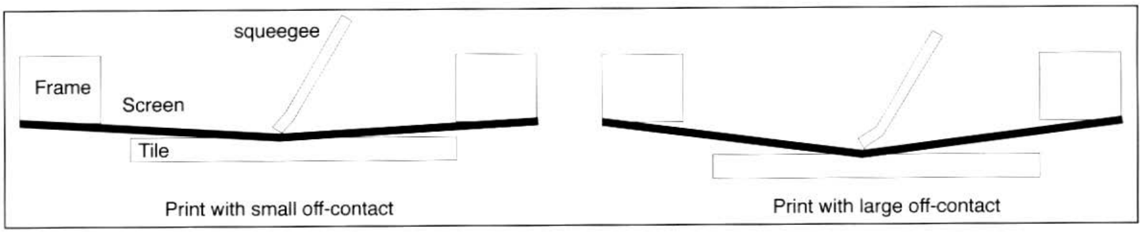

Figure 5. *Schematic of squeegee force in terms of off-contact.*

An experiment conducted by Mark A Cougray [COU 96] showed the differences in tension produced by squeegee pressure to which a screen, having a static or nominal tension of 22 N/cm, is subjected (Figure 6). The study revealed the differences between two different "*off-contacts*", reading the specimens at differing distances from the screen frame.

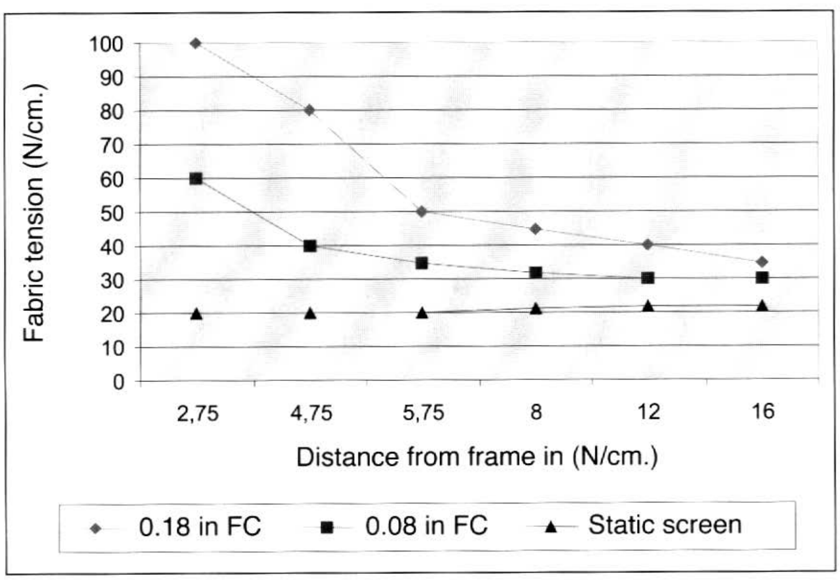

Figure 6. *Differences in tension produced by squeegee pressure to which a screen, having a static or nominal tension of 22 N/cm, is subjected. [COU 96]*

It can be observed that "off-contact" is in any case a factor that affects shades. How this factor affects shades was studied in three steps; first together with screen tension, secondly with ink viscosity, and finally by including the parameters in a more general regression model.

```
R-squared = 96,1798 percent
```

```
R-squared (fitted by f.d.) = 95,3308
percent
Statistical STD error = .393909
Mean absolute error = .252649
Durbin-Watson statistic = 1.57285

MEDO = 60,7633 - 0,77363*FCA -
1,36339*TINT
```

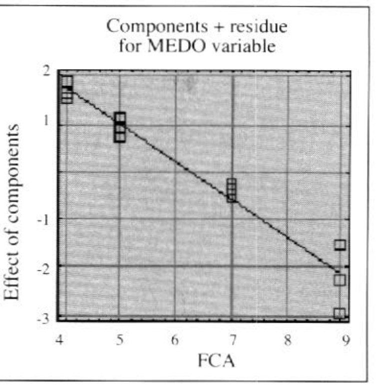

Figure 7. Regression model between variation of ink viscosity and off-contact. Analysis was performed at a constant screen tension of 20 N/cm.

A model was thus obtained (Figure 7) which explains 95 % of the variations in L as a result of variations in *"off-contact"* and ink viscosity. The model is valid for a tension of 20 N/cm, and has a significance of 80% at a screen tension of 25 N/cm, with a slight variation in the regression equation. (MEDO = 60,1371 - 0,712133*FCA - 1,95527*INK).

```
R-squared = 71.4579 percent
R-squared (fitted by f.d.) = 68.7396 percent
Statistical STD error = .989002
Mean absolute error = .722162
Durbin-Watson statistic = 1.59241

MEDO = 60,5937 - 0,559145*FCA - 0.270225*TP
(FCA=FCB)&(TINT>=2.5)
```

Table 3. The regression study between the mean colour value of the specimen (MEDO) with off-contact and screen tension explains 68% of the arising shades. The study was run with viscosity values equal to or larger than 2.5 minutes.

Multiple correlation analysis between the variations of L, produced by variation in *"off-contact"* and squeegee tension, explain 68% of the variations in L (Table 3). The model is valid for viscosity values exceeding 2.5 minutes. On integrating 1.5-min viscosity in the model, the model's significance drops to 40 %, even though the linear regression equation is quite similar.

```
R-squared = 65.8032 percent
R-squared (fitted by f.d.) = 61.3907 percent
Statistical STD error = 1.18512
Mean absolute error = .884081
Durbin-Watson statistic = 1.33931

MEDO = 54.5969 - 0.552349*FCA + 0.196747*TP + 2.01567*TINT -
0.161491*TINT*TP
```

Table 4. The derived regression model is a linear model. It can be said that 61% of the variations are included in the model, and it shows how each factor affected the mean L value. A rise in viscosity (measured in minutes) entails lightening of the printed shade; a rise in tension lightens the colour of the tile and an increase in "off-contact" darkens it.

Table 4 quantifies the variations produced by changes in tension or ink viscosity. The model was calculated for a mean *"off-contact"* of 7 mm. The table shows that *"off-contact"* and screen tension both give rise to shades in the tile in the same direction. A rise in *"off-contact"* lowers mean colour and a rise in screen tension also lowers mean colour.

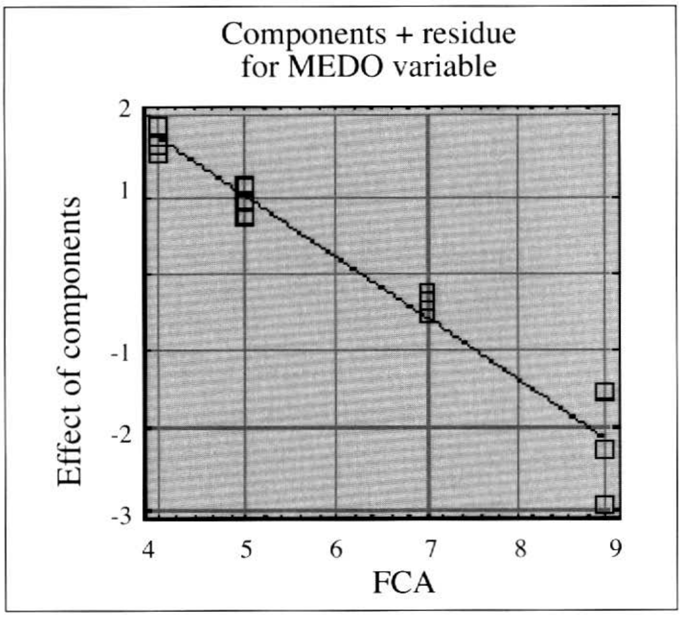

Figure 8. *Plot of the deviation between the multiple regression equation indicated in Table 7.4, with predicted data (straight line) and experimental data (points).*

The range of variation in *off-contact* can fluctuate in ceramic screen printing applications from about 4 to 10 mm, while screen tensions range from 8 to 20 N/Cm.

If the two variables are crossed, a series of combinations are obtained, which allow studying variations in colour. On setting a series of possible combinations, the data detailed in the following table were obtained:

Off-contact (mm)	Screen tension (N/cm)	Modification of the L value
4	20	-5.439216
5	18	-5.668583
6	16	-5.89795
7	14	-6.127317
8	12	-6.356684
9	10	-6.586051
10	8	-6.815418

It can be observed that combining both values according to this table produced a negative colour difference of 1.4 in L.

It should be noted that the theoretical objective is to obtain differences that tend to raise the value of L, since that means less ink deposit or less ink spread and thus a reduction in dot gain.

If the data are crossed, the sensitivity or increase in L arising for this reason can be analysed. Assuming a print is being made with a 16 N/cm screen, at an "*off-contact*" of 6 mm, if the screen breaks and is replaced by one of 12 N/cm, having an off-contact of 8 mm, a change in L of 0.45 points is predicted. If the "*off-contact*" is not adjusted but kept at 6, the change in L becomes 0.65.

3.2. STUDY OF VISCOSITY

Correlation coeficient = -.98661 **R-squared = 97.3399 percent** Statistical STD error = .53185 **MEDO = 60,7 - 2.97857*TINT** (FCA=FCB)&(FCA=4)&(TP=16)

Table 5. *The regression study between the L value at a point on the tile and viscosity fits variation to 75% in a linear way. Each unit of viscosity affects the value of L in the end colour in 2.98 points. The study was run for a screen tension of 16N/cm and an off-contact of 4 mm.*

MEDO = 60.7 - 2.97857*TINT
R-squared = 97.3399 percent
(FCA=4)&(TP=16)

MEDO = 56.2225 - 1.08714*TINT
R-squared = 99.9315 percent
(TP=20)&(FCA=5)

There is a great variability between regression models produced by changes in screen tension. Low screen tension heightens the shades produced by variations in viscosity.

That is to say, there appears to be a correlation between ink viscosity and screen tension. This correlation was included in the final linear regression model

The regression model between percent colour variations in the specimens is a linear model; a rise in viscosity negatively affects this percentage, i.e., the value of L drops and its proximity to black increases.

Correlation coefficient = -.948996
R-squared = 90.0593 percent Statistical STD error = .910442 **MEDO = 60.1238 - 2.62029*TINT**

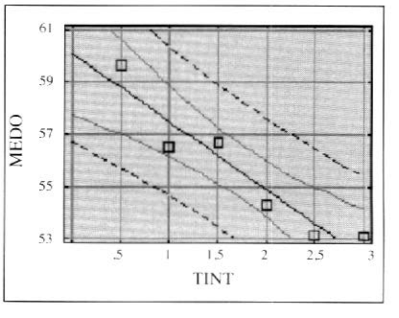

Figure 9. *Analysis of linear correlation between viscosity and variation in printed colour. Raising viscosity produced a darker image.*

A rise in viscosity involves a drop in L, i.e. the printed colour is darker. This occurred in the part of the study conducted for a specific screen.

The tests carried out with a series at rising viscosity, with a steady screen tension of 20N/cm and off-contact of 5 mm, revealed a clear linear correlation between printed colour and ink viscosity (Figure 9).

3.3. STUDY OF THE ANGLE

```
Correlation coefficient = .936516
R-squared = 87.7063 percent
Standard Error of Est. = 1.32919

MEDO = 40.9308 + 0.169736*ANGLE
```

Table 6. *A regression model between mean colour value in terms of the angle was derived for sharp squeegees. A greater angle meant an increase of 0.16 per degree in the value of L, i.e., the colour lightened as the attacking angle grew.*

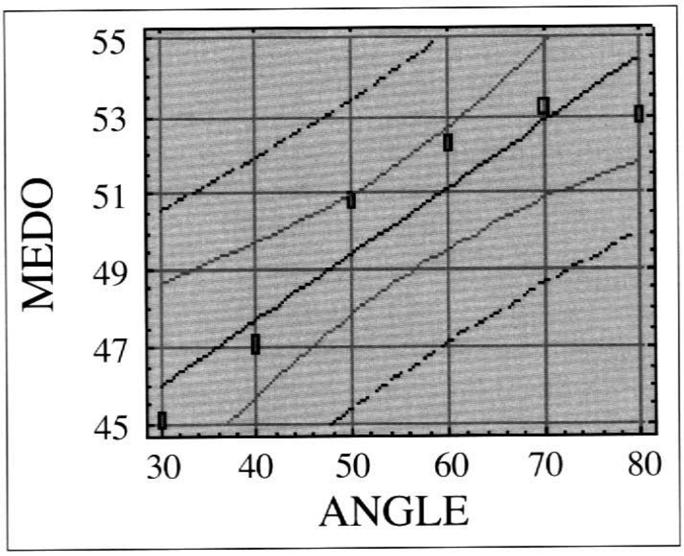

Figure 10. *Plot of the experiments involving the appearance of shades as a function of angle. Fit by regression straight line.*

The linear model proposed exhibited a high probability value, however, a curve fitting a second-order equation could possibly be obtained in the points. This study is set out in the following table (Table 7).

```
R-squared = 97.9265 percent
R-squared (itted by f.d.) = 96.5441 percent
Statistical STD error = .630334
Mean absolute error = .359833
Durbin-Watson Statistic = 2.97173

  MEDO = 30,0878 + .606102*ANGLE-.00396696*ANGLE^2
```

Table 7. *Polynomial regression analysis between MEDO and angle. Figs. 10 and 11 already show how it is possible to fit the relation between mean colour and angle to a curve. This fit is observed to be much more accurate, even describing 96% of the variation in colour. MEDO is the average value of four points corresponding to the dark pattern in the four corners of the tile.*

The squeegee used for the experiment was a sharp squeegee with a 90-deg. edge. A smaller angle raises contact surface, forces more ink through or raises the contact area between the fabric and the surface to be printed so that the dot spreads more.

As Table 7 shows, there was an exponential relationship between mean colour of the tiles and squeegee angle, provided the squeegee was sharp. This relationship did not exist when the squeegee was worn. This could be because a worn squeegee profile might be more or less rounded so that the attacking angle remained constant as Figure 12 reveals.

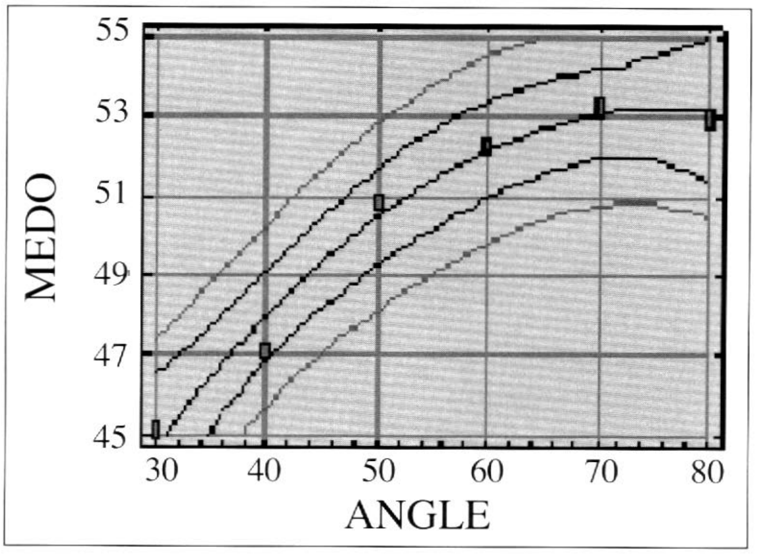

Figure 11. The data in Table 7 yield the regression curve between mean colour value and squeegee angle.

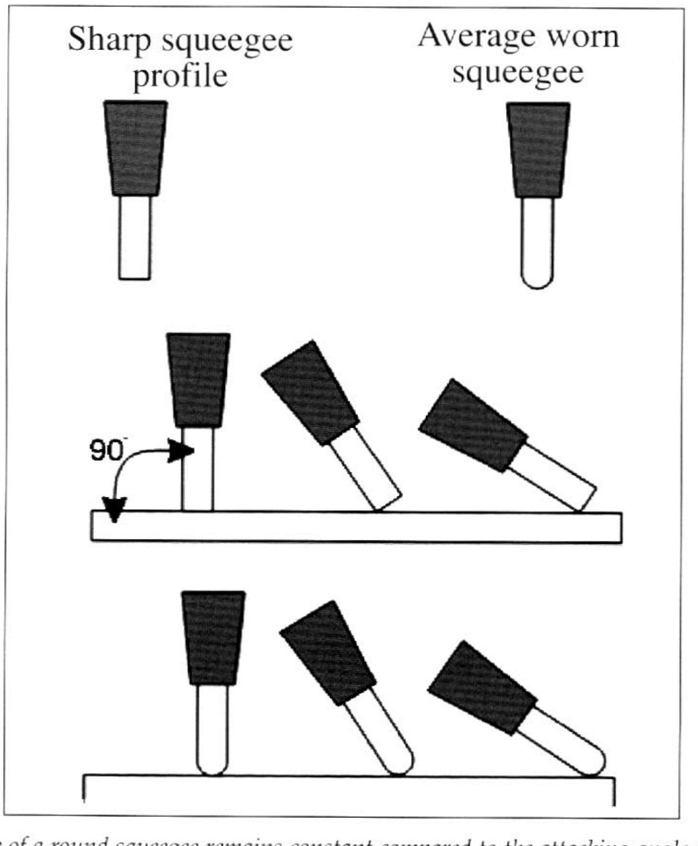

Figure 12. The angle of a round squeegee remains constant compared to the attacking angle of a sharp squeegee.

Using the following equation, calculating its derivative and setting it at zero, the curve's maximum point can be found. This is precisely the optimum point since it is where the variations in angle least affected specimen colour.

$$MEDO = 30.0878 + .606102*ANGLE-.00396696*ANGLE^2$$

$$0 = 0.606102-2*0.00396696*ANGLE$$

$$Angle = 76,4^{\circ}$$

A change in the angle around this value (between 71.4 and 81.4) produces a change in L of 0.00049488, compared for instance to a change between 50 and 60 degrees in the angle, which produces a change in L of -1.697364.

Up to this point the study has dealt with differences in colour between screen-printed tiles. The study was then completed by an analysis of the internal variability of shades, i.e., the appearance of shades or colour differences in one same tile. A study conducted in this sense is summarised below.

Joint analysis of the effects of each variable. Relative importance.

	FACTOR PER UNIT DIFFERENCE OF L	FLUCTUATION OF THE VARIABLE AND COLOUR DIFFERENCES IN THE GENERAL EQUATION	FLUCTUATION OF THE VARIABLE AND COLOUR DIFFERENCES IN THE SPECIFIC EQUATION	OPTIMUM MARGIN
FCA	0.27	(3-10 mm) 0.9-2.7	0.6	Minimum 4
FCB	0.21	(3-10) 0.6-2.1	0.2	Minimum 4
FCB-FCA	0.23	(1-5 mm.) 0.2-1.2	1.2	Maximum 9
VISCOSITY	0.57 per minute	(1.5 and 3.5 min.) 0.85-2	3.1	Minimum 1.5
SCREEN TENSION	0.0756557 per N/cm.	(10-25 N/cm) 0.7-1.9	1.2	21.2 N/cm.
ANGLE	0.0530814 per degree	(40-80 degrees) 2-4	2	59.6°

Differences in colour or shades in one same tile were evidently minor. The study highlights the need to reduce off-contact, to use high screen tensions and as some authors have suggested [COU 89, PEY 92], the need to limit fluctuations owing to ink flowability, whose recommended values lie between one and two minutes.

4. CONCLUSIONS

The following equations were obtained, with their degree of significance. The equations are all valid. It is to be noted that in those in which a single parameter appears, the others have been kept steady.

The effect on the reference colour fitted linear models in the variation range of the parameters used in the experiment.

This does not mean that the models are linear, and that it is therefore impossible to obtain optimum dots, but that amongst the most common values used industrially, the variations that affect shades are linear.

The extent of the variations for each factor can be deduced from the table, and in each case the influence of each factor was significant.

There was however a percentage production variation that was not described in the model, which could not be assessed by the data or experiments performed, but the equations presented manage to explain up to 99% of the variability, which indicates that an important source of shades produced in screen printing has been identified.

GENERAL TEST			
Variable	**MEDO Equation =**	**Significance (R^2)**	**Limitation**
FCA	57.8479 - 0.884068*FCA	96.3522	TP=20N/cm INK= 2.5 min.
FCA INK	60.7633 - 0.77363*FCA - 1.36339*INK	95.3308	TP=20 N/cm.
FCA INK	60.1371 - 0.712133*FCA – 1.95527*INK	80	TP=25 N/cm
FCA TP	60.5937 - 0.559145*FCA - 0.270225*TP	68.7396	INK>=2.5
INK	60.7 - 2.97857*INK	97.3399	FCA=4 TP=16
INK	56.2225 - 1.08714*INK	99.9315	TP=20 FCA=5
FCA TP INK INK*TP	54.5969 - 0.552349*FCA + 0.196747*TP + 2.01567*INK - 0.161491*INK*TP	61.3907	
SPECIFIC INK AND ANGLE TESTS			
INK	60.1238 - 2.62029*INK	90.0593	
ANGLE	40.9308 + 0.169736*ANGLE	87.7063	
ANGLE	30.0878 + .606102*ANGLE-.00396696*ANGLE^2	96.5441	

The above equations and following points represent the conclusions of the study:

- "Off-contact" is the most important parameter in shades or colour variation arising in screen-printed tiles. A rise in this value means a drop in L.

- Raising "off-contact" is usually motivated by lower screen tension. These values balance out variations in colour.

- Higher viscosity produces a drop in L.
- There is a squeegee angle around which shades are minimised. The value was 76.4 degrees.
- There is a relation between screen tension and ink viscosity, which affects shades in screen prints.

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