STUDY OF SCREEN-PRINTING APPLICATION CONTROL VARIABLES AND THEIR INFLUENCE ON SHADES IN TILE

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ABSTRACT

The differences in colour (shades) arising in single-fired ceramic tile manufacture, which affect an important part of production, stem from the variability of the raw materials and the manufacturing process in each process stage.

One of the most important aspects involved in tackling the study of this complex problem has been that of designing a data acquisition and assessment system on the effect that different process variables have on shades.

As a result of the study, courses of action can be defined to which priority should be given.

This paper forms part of a general study on the appearance of shades, which is being undertaken by TAULELL, S.A. in cooperation with the Instituto de Tecnología Cerámica (ITC).

This study aims to offer a concrete vision of the influence of the screen-printing variables involved in ceramic tile decoration.

The study focuses on the influence of the screen-printing application variables in the glazing line, on their control, and on the assessment of the shades that arise in this process step.

This has been done by fitting a screen-printing facility that is usually employed in industrial tile decoration, with appropriate systems for evaluating the control variables in real time; their evolution has been analyzed over time under normal working conditions, and finally, the effect of certain significant variables was studied.

1 INTRODUCTION

One of the characteristics that noticeably affects tile quality is its surface appearance, which is mainly defined by texture and colour.

This present work is part of a study undertaken by TAULELL, S.A., in cooperation with the Instituto de Tecnología Cerámica (ITC), of the factors upon which differences in colour (shades) depend in ceramic wall and floor tile manufacture, and whose general objective has been the suppression of shades in single-fired tile.

Numerous studies have set out (1,2,3) the wide range of factors upon which final tile colour depends. They particularly relate to changes in the characteristics, across time, of the different materials making up the composition of the body, engobe, glaze and/or screen-printed decoration, as well as the manufacturing process variables.

In one of the first stages of the study, a data acquisition system was designed for collecting the variations in colour that were observed during industrial tile sorting together with the alterations that had arisen in the fundamental variables.

On analysing the data obtained on the different factors involved, it was inferred that the alterations in the variables associated with the screen-printed decoration had the greatest impact on shades in tile (screen-printing currently being the main tile decorating method), manufactured by single firing (this represented 40-60% of the problem, depending on the model involved).

Screen-printing variables are usually classified for study as follows: the ones relative to the screen-printing ink (vehicle, pigment, screen-printing base, additives, preparation process, etc.); those relating to the printing screen itself (frame, fabric, emulsion, processing conditions, etc.); and finally the ones corresponding to application in the glazing line (printing machine, ambient conditions, etc.).

Some of the aspects related to the preparation and homogenization of screen-printing inks (4), the importance of the rheological parameters (5,6,7), and the processing of the printing screens (8,9,10,11,12,13) have been dealt with elsewhere.

2 OBJECTIVES

This paper focuses on an analysis of the screen-printing application control variables in the industrial glazing line, and how they impact the appearance of shades. The following were the main objectives of the study:

- Design of an experimental setup capable of adequately recording the alterations arising in the variables that control the screen-printing application.
- Assessment of the influence of the screen-printing application control variables on tile colour.
- Quantification of the admissible maximum tolerance in the essential application variables.

3 EXPERIMENTAL DEVELOPMENT

3.1 CONTROL VARIABLES MEASURING ASSEMBLY

This work was carried out with an OMNIS DUE screen-printing machine, set in the industrial glazing line, equipped with a side belt feeding system.

The selection of each measuring element of the different variables was done based on an analysis of the frequency of the phenomenon to be determined, the measurement interval involved and the required accuracy in each variable.

The elements selected for assessing each variable are detailed below.

3.1.1 Ink temperature in the screen-printing machine

The measuring element used was a platinum thermal resistance (PT100) with a nominal accuracy of ±0.2°C, which was kept in constant contact with the ink on the printing screen during the experimentation.

3.1.2 Tile surface temperature in the glazing line

A THERMO-HUNTER model BA-32T optical pyrometer was used, which is sensitive to infrared radiation. The pyrometer was installed above the glazing line, in an area immediately preceding tile entry to the decorating facility.

3.1.3 Force exerted on the squeegee

The sensors used for determining this value were two EF-13 flexion load cells, with a measuring range of 0 to 13 kgf, and an error of 0.3% in respect of their scale background.

3.1.4 Squeegee position and velocity

The transducer employed was a TEMPOSONIC MT-500 position and velocity sensor, which monitored these variables during the movement of the squeegee. The measuring element used is capable of detecting speeds ranging from 0 to 10 m/s.

3.1.5 Ink viscosity in the feeding tank

This variable was intermittently determined by means of a BOHLIN V-88 rotational viscometer, keeping ink temperature steady during testing.

3.1.6 Tile curvature

The assembly used to assess tile curvature determines the distance from the central part of the tile to a reference plane (sag). The sliding micrometric sensor used has a maximum travel of 10 mm and an accuracy of 1 mm.

3.1.7 Distance from the screen to the reference plane

This value was measured by placing a graduated angle between the screen frame and a reference surface. The depth to which the angle can enter is proportional to the distance between the screen and the reference surface.

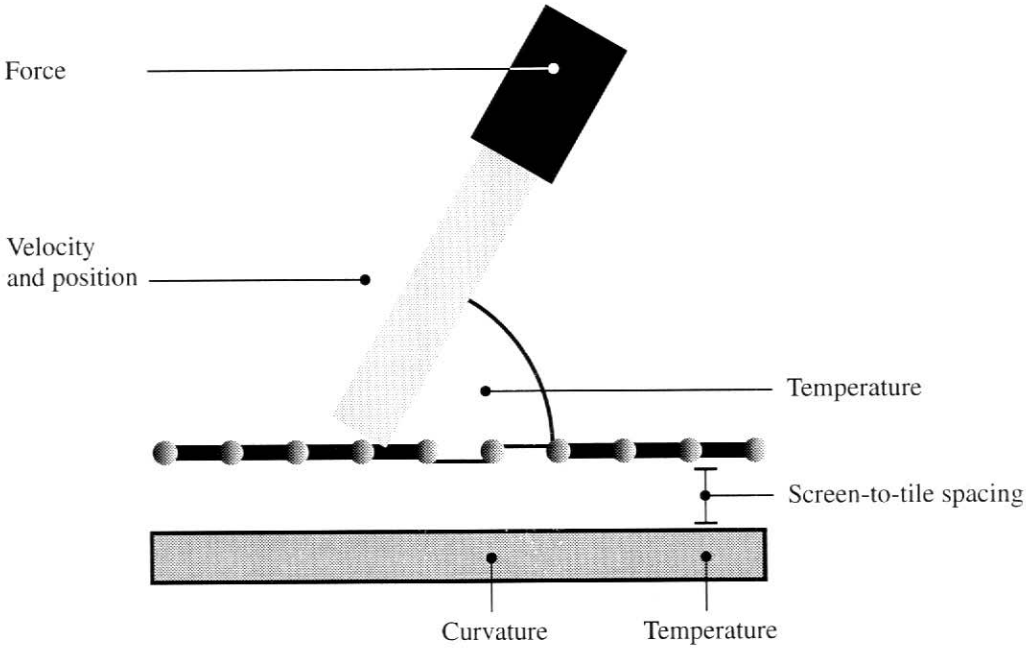

***Figure 1**. Schematic of the measuring assembly used.*

3.2 MATERIALS

Three industrial inks were employed, which are used in porous single-fired wall tile manufacture, made up of a screen-printing base (40-60 %), pigment (5-20 %), and a screen-printing vehicle (40-60 %). These inks were respectively referenced: GREY, PINK and BLUE.

The preparation of the inks was carried out by proportioning, mixing and dispersing the pigment and base in the vehicle, subsequently micronising in a bead mill, which in every case yielded a maximum particle size below 30 micrometers.

Ink density was then adjusted to application conditions, and the viscosity curve was determined under these conditions.

The screen-printing application, in the industrial line was done on 20x25 cm porous redware wall tile, which had previously been pressed, dried, engobed and glazed.

3.3 ASSESSMENT METHOD OF PRINTING RESULTS

Screen printing took place with a 60x80 cm screen, on which a grid had been drawn dividing the total printing area (20x25 cm) into 3x3 rectangular screen areas. The fabric used had 77 threads/cm and a weave of 20 points/cm. The tension of the screen used was 10 N/cm.

One variable was then modified in each experiment, keeping the remaining essential variables constant, and runs were made on 15 tiles, selecting the last five of each test, after the constancy of the application had been verified with the first 10 impressions.

After printing, the tiles were fired at an industrial kiln and the results were assessed by means of a MACBETH COLOR EYE 7000 colorimeter, determining the chromatic coordinates L*, a*, b* (CIELAB).

The difference in colour was determined as DE calculated from the data of the mean chromatic coordinates of each set of tiles in respect of a reference that is detailed in each experiment.

4 RESULTS

4.1 VERIFICATION AND PREPARATION OF THE TESTING ASSEMBLY

The results are set out below of the measurements performed in the industrial glazing line in the course of several non-consecutive days, during which the proper working of the installed measuring assembly was verified.

4.1.1 Analysis of the positional cycles, velocity and force of the squeegee.

The flat screen-printing process (commonly used in the ceramic branch) is divided into two stages. In the first, the ink is spread over the screen, and in the second, the actual application to the tile takes place.

In the application, the squeegee exerts a combination of forces: moving-dragging the ink across the screen, pushing the ink through the screen, and a bringing the screen into contact with the tile surface, thus effectively transferring the ink to the tile.

In general, these forces act by elastically deforming the squeegee, generating a consequent reaction on the squeegee holder, so that this part of the equipment can be assumed to integrate the different forces that arise in the tile-printing operation.

Fig. 2 shows the evolution of the position, velocity, and force detected during a printing cycle run.

In the position curve (curve (A) in the graph), three characteristic points can be identified. Point (1) corresponds to the start of the tile decorating cycle, and coincides with the moment at which the squeegee starts spreading ink over the screen. Point (2) represents the greatest outward travel of the squeegee, since this marks the point at which the squeegee starts its return stroke back to the starting position, reached at the moment represented by point (3).

In curve (B), the cycle of squeegee velocities has been plotted during a single application. Five characteristic points can be distinguished: (point 4), corresponding to the start of the cycle (ink distribution step), point (5), which coincides with the peak velocity value (intermediate position between points (1) and (2)). Velocity changes from point (6) onwards, whose position coincides with maximum outward travel. It is from this moment on that the actual decorating step starts, reaching peak velocity in this step at point (7), and ending at point (8).

Finally, curve (C) shows the register of forces obtained during a full decorating cycle. A gradual increase in force can be observed during the ink distribution step. In the area of the cycle corresponding to the squeegee changeover, an abrupt swing appears in the recorded force. After changing squeegees, an sharp fluctuation can be observed in the recorded force values. This value drops appreciably towards the final decorating step, which is characterized by a rapid descent in the force values observed.

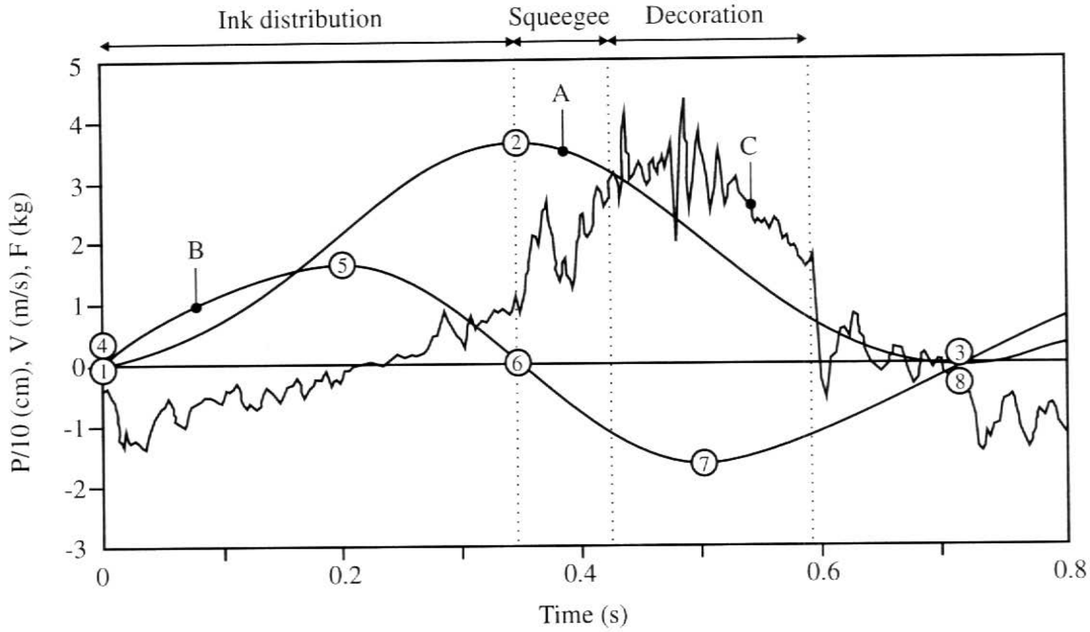

Figure 2. Evolution of the squeegee position, velocity, and force during a printing cycle.

P= Squeegee position
V= Squeegee velocity
F= Force registered on the decorating squeegee

Table 1 lists the variation intervals of these parameters.

Table 1. Variation interval of squeegee position, peak velocity and mean force.

Parameter	Value
Maximum travel (cm)	37.15-37.17
Peak velocity (m/s)	2.41-2.46
Mean force(1) (Kg)	3.03-3.16

(1).In the decorating area during printing.

4.1.2 Temperature variation

Fig. 3 shows a plot of the variation in ink, tile and ambient temperature during the experiments run to check the data gathering systems.

It can be observed that tile temperature (curve 1) was higher than the other two temperatures (ink and ambient). As far as the temperature of the ink spread on the screen is concerned (curve 2), it was found that the swings in temperature were caused when ink from the feeding tank was added, with ink peak temperature on the screen coinciding roughly with the feeding tank ink temperature. After this addition, the ink then cooled down to close to ambient temperature (curve 3).

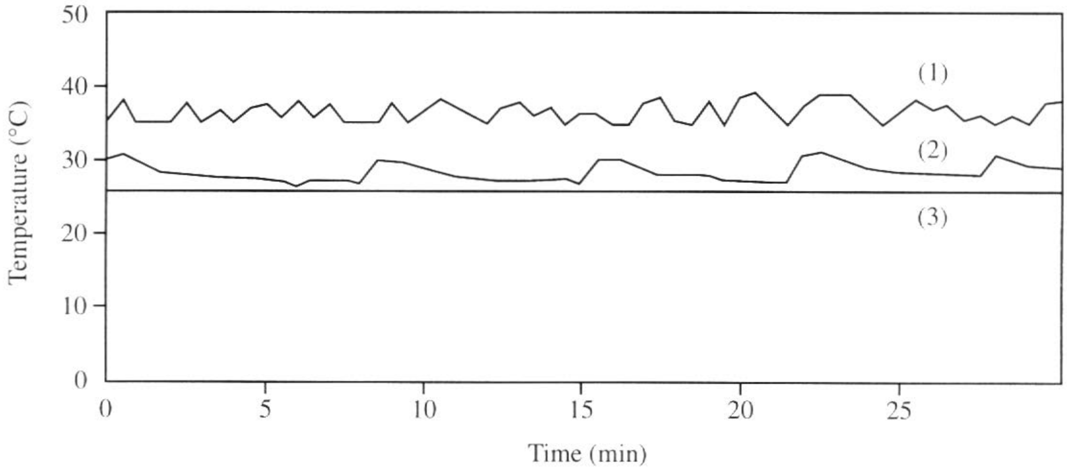

***Figure 3.** Evolution of tile (1), ink (2) and ambient (3) temperatures.*

4.1.3 Distance of the screen to the tile

It was shown that the distance at which the printing screen remained when it was placed in the printing machine varied, under the usual operating conditions, by between 4-8 mm.

4.1.4 Curvature of the unfired tile

The data obtained allowed determining the values for the mean sag of the tiles and their standard deviation. These were as follows:

- Mean sag: 0.169 mm
- Standard deviation: 0.070 mm

4.1.5 Ink viscosity

Fig. 4 shows a plot of the viscosity of the inks used at a temperature of 25 °C.

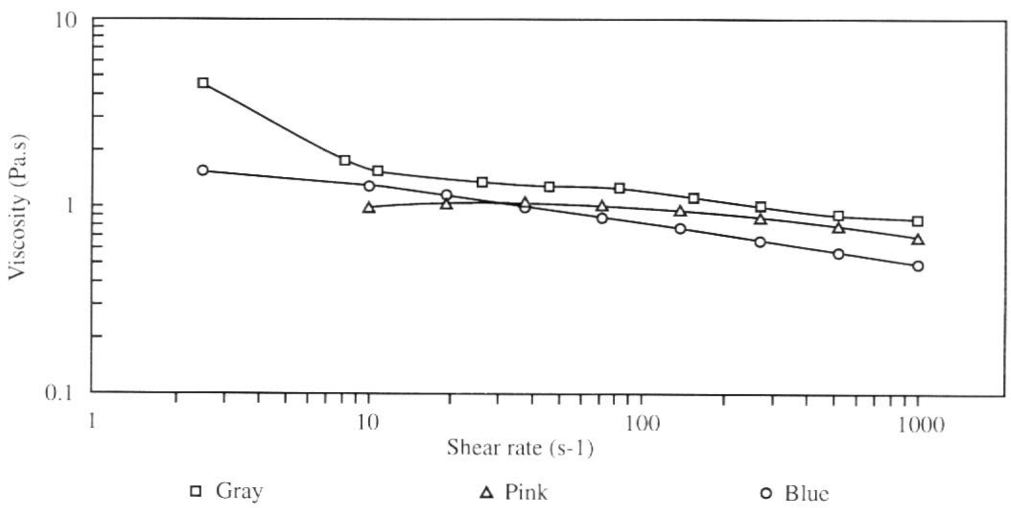

***Figure 4.** Viscosity curves of the GREY, PINK and BLUE inks.*

4.1.6 Summary of the variations observed

Table 2 lists the variation intervals of the values found for the studied variables.

Table 2. *Variation interval of the assessed parameters*

Variables	Variation
Tile temperature (°C)	37-40
Ambient temperature (°C)	31-25
Ink temperature on the screen (°C)	28-33
Ink temperature in the feeding tank (°C)	25-33
Maximum travel (cm)	37.15-37.17
Peak velocity (m/s)	2.41-2.46
Mean force (kg)	3.03-3.16
Screen-to-tile spacing (mm)	4-8
Mean sag (mm)	0.099-0.239
Viscosity[2] (cP)	505-880

[2]. *Measured at a shear rate of 1000 s^{-1}.*

4.2 Influence of the printing application control variables on tile colour

Some of the variables assessed in the previous section varied slowly, as was the case of ambient, tile and feeding tank ink temperatures. The experiments, whose results have been set out in the following, were performed while keeping these temperatures virtually constant.

On the other hand, it was shown that there were only minor variations in unfired tile curvature under standard operating conditions, compared to the spacing between the tile and the printing screen, so that the experimentation was conducted at practically constant curvature of the tile.

4.2.1 Effect of ink density

Screen-printing ink density basically affected two screen-printing parameters: viscosity and solids concentration. Several workers report (14,9) that increased viscosity can affect the resulting impression in two ways, depending upon the magnitude of this parameter. Thus, when viscosity rises, so does hydrodynamic pressure, which makes the ink pass through the screen.

This favourable printing effect is counteracted by the flow resistance that occurs as a result of increased viscosity.

The other parameter relating to the variation of density, namely solids concentration, has a marked affect on the resulting impression, since the variation in ink density is directly related to its solids content, which determines the deposition of printed ink.

The results obtained have shown that raising ink density also raised the colour intensity of the prints, together with noticeable differences in colour, as Fig. 5 shows. These differences may be basically attributed to the variation in the pigment concentration within the ink, since as the following sections will show, the variation of hydrodynamic pressure had less effect on colour.

Fig. 5 depicts the difference in colour (DE) observed as a function of the ink densities used. The difference in colour was calculated from the determination of the chromatic coordinates (15) (L^*, a^*, b^*), taking the ones corresponding to the tiles printed with each ink (GREY, PINK, and BLUE) at the lowest tested density (1.45 g/cm^3). It can be observed, that the tiles printed with BLUE ink were the ones that underwent the greatest variation, whereas the least variation was associated with the ones printed with GREY ink. In any case, the differences in colour were visually perceivable.

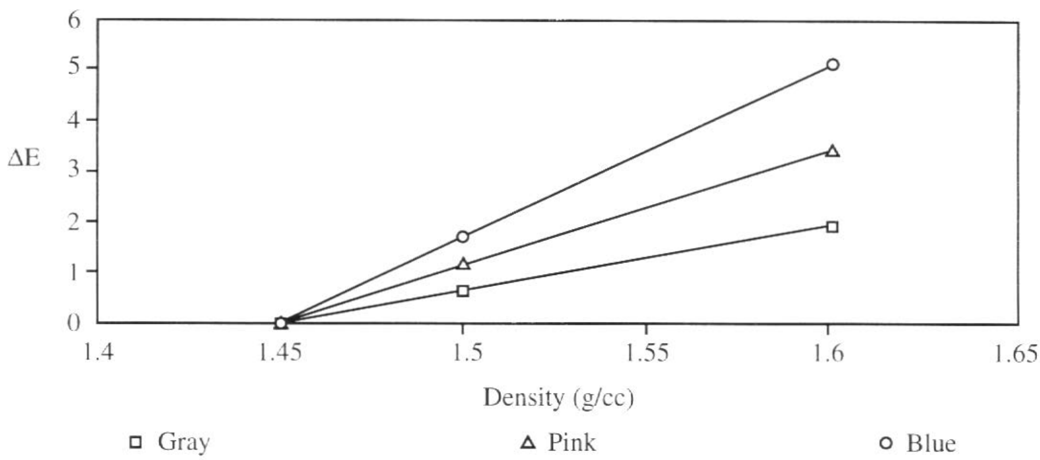

Figure 5. *Influence of ink density on screen-printed colours*

4.2.2 Effect of the screen-to-tile spacing

The screen-to-tile spacing affects the deformation that the squeegee undergoes when it presses the stretched fabric against the tile body, at the angle formed by the fabric and the squeegee during the printing application, and affects the velocity at which the fabric is separated from the tile after the application.

Table 3 shows the chromatic coordinates for inks GREY, PINK, and BLUE, and the difference in colour of the impressions made at a screen-to-tile spacing of 4.5-6.5 cm, taking the values of the chromatic coordinates for the calculation of the difference in colour, which corresponded to the tiles whose screen-to-tile spacing was 4.5 cm, as reference values.

On raising the screen-to-tile spacing, tile colour intensity was observed to decrease.

Table 3. *Effect of the screen-to-tile spacing on the colour*

Ink	Distance (mm)						
	4.5			6.5			
	L^*	a^*	b^*	L^*	a^*	b^*	DE
GREY	86.16	-0.89	3.00	86.17	-0.91	3.00	0.03
PINK	85.19	1.60	2.94	85.72	0.88	2.83	0.91
BLUE	78.21	-0.34	-7.26	79.99	-0.66	-5.2	2.74

4.2.3 Effect of printing velocity

The velocity of the squeegee during the printing application basically affects the hydrodynamic pressure that forces the ink through the screen, so that on raising this velocity, pressure also rises on the ink, which favours the printing application. However, if the squeegee velocity is too high, the contact time between screen and tile may be insufficient to allow all the ink to fully pass through. Under extreme working conditions, at a high squeegee velocity, acting on a dense, highly viscous ink, this may cause the squeegee to slide across the ink, separating the squeegee from the screen, and producing an excessive deposition of ink (14).

Table 4 details the chromatic coordinates and colour differences as a function of the peak velocity of the printing application (for the calculation of the difference in colour, the values of the chromatic coordinates corresponding to the tiles printed at the lowest speed were taken as reference values).

In the squeegee velocity interval tested, it was shown that the variation in tile colour on raising printing velocity was hardly noticeable in the GREY and PINK colours, while exhibiting a greater colour difference in the tiles printed with BLUE ink.

Table 4. *Effect of printing velocity on colour*

Ink	Peak velocity (m/s)						
	2.41			2.82			
	L^*	a^*	b^*	L^*	a^*	b^*	DE
GREY	86.16	-0.89	3.00	86.04	-0.86	2.97	0.12
PINK	85.19	1.60	2.94	85.46	1.21	2.86	0.48
BLUE	78.21	-0.34	-7.26	76.97	-0.14	-8.32	1.65

4.2.4 Effect of squeegee pressure

The pressure that the squeegee exerts on the screen fabric and on the tile is mainly directed at bringing the fabric (whose apertures are full of ink) into contact with the tile, for ink transfer to take place.

However, when squeegee pressure is modified, the angle which the squeegee makes with the tile during printing may also be modified (owing to the elastic nature of the squeegee), which may give rise to variations in the ink deposition.

Table 5 lists the values of the chromatic coordinates and colour differences (in respect of the tiles printed at the lowest pressure), as a function of the mean force exerted by the squeegee during printing. It was shown that in general, the differences are much less important than the ones observed in the foregoing cases. These differences were virtually visually imperceptible.

Table 5. Effect of force on colour

Ink	Mean force (kg)						
	3.04			4.94			
	L^*	a^*	b^*	L^*	a^*	b^*	DE
GREY	86.16	-0.89	3.00	86.00	-0.85	3.00	0.16
PINK	85.19	1.60	2.94	84.97	1.76	2.87	0.28
BLUE	78.21	-0.34	-7.26	78.13	-0.37	-7.07	0.21

4.2.5 Assessment of the sensitivity of colour change to the variation of the studied variables

In order to assess the perceivability of the colour differences that arise in each of the tested inks (GREY, PINK and BLUE), on varying the printing application control parameters, a visual comparison was made of the tiles that had been printed with different intensities of the GREY, PINK and BLUE inks. The printed tiles were visually inspected by qualified technicians under uniform lighting conditions.

After observing these tiles, they were classified according to shades and their chromatic coordinates were determined, so as to allow assessing the minimum difference in colour (DE) that was visually perceivable for each colour.

Table 6 sets out the results of this classification. It shows that the minimum visually perceivable difference in colour depends on the colour involved. Thus, the admissible variations in colour DE in impressions obtained with the BLUE ink are much greater than the admissible ones with the PINK and GREY inks. Several authors (15) have dealt with this aspect of visual perception, without finding a simple relationship between the calculated colour variations and the actually observed ones.

Table 6. Minimum observed colour difference.

Ink	Colour difference (DE) equivalent to a classification shade
GREY	0.2
PINK	0.4
BLUE	2.0

The data summarized in Table 6 and the data on colour variation as a function of the studied variables (density, screen-to-tile spacing, velocity and printing force), have allowed calculating (Table 7) the modification (represented by the symbol D in this table) of each variable that would produce a visually perceivable change in each of the studied colours.

Table 7. Sensitivity of colour to variations in the printing control variables.

	GREY	PINK	BLUE	Control limit
Δ(Density) (g/cm^3)	0.02	0.02	0.05	±0.01
Δ(Spacing) (mm)	16.00	0.88	1.46	±0.5
Δ(Velocity) (m/s)	0.66	0.33	0.49	±0.05
Δ(Force) (kg)	2.37	2.71	18.09	<0.5[(3)]

(3). This variable is not currently determined on an industrial scale, the value given is an estimate based on the regulating system

The table shows that the variable whose control was most critical was the density of the screen-printing ink. The screen-to-tile spacing, printing velocity and force, exhibited sufficiently well-adjusted control margins on an industrial scale, which were narrower than the variations that would need to arise for a visually perceivable colour difference to be produced.

5 CONCLUSIONS

The results obtained allow drawing the following conclusions:

1. A system has been designed, which allows gathering information on the state of the fundamental variables that control screen-printing of tile on an industrial scale.

2. It has been shown for the tested inks, that the parameter that most affects shades is ink density. The screen-to-tile spacing, and printing velocity also have a considerable impact on shades. However, the force exerted by the squeegee during printing does not seem to have any appreciable effect.

3. The minimum visually perceivable colour difference (DE) has been quantified for each ink used in this study. The sensitivity of the control of screen-printing ink density, as it is usually determined in manufacturing facilities, is actually quite close to the minimum value that may give rise to an appreciable change in colour. The remaining studied variables have a sufficiently wide tolerance margin for the control systems that are currently in place to detect their variations and prevent shades from arising.

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