EFFECT OF PRINTING CONDITIONS ON THE RADIANT BEHAVIOUR OF CERAMIC TILES

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ABSTRACT

In this work, glazed porcelain tiles were digitally printed in binary and grey scale modes using different inks and coverages. The radiant behaviour of the printed inks was then studied over the entire solar spectrum. In addition, the solar reflectance was correlated with the chromaticity coordinates, obtaining diverse empirical models that can be used as a tool to estimate the radiant behaviour of any design only from these coordinates.

Results showed, on the one hand, that it is better to use warm colours such as magenta and yellow as they behave better and, on the other hand, that an increase in the percentage of ink coverage decreases the solar reflectance of all samples. Moreover, it would be advisable to print in grey scale since, for the same solar reflectance, darker surfaces are obtained with this printing mode. Finally, the suitability of the empirical models was successfully verified by using them in the estimation of the solar reflectance of industrial tiles with high accuracy.

1. INTRODUCTION

The residential sector (buildings and residences) is a key sector in the energy context, both at national and European level, due to its significant energy consumption, especially for cooling purposes [1,2]. When a certain building surface or constructive element is exposed to solar radiation, it absorbs part of the irradiated energy, increasing its temperature. Then, a portion of the absorbed energy is released through thermal emission and convection, but the rest is stored in the element itself due to its high thermal storage capacity [3]. This heat gain, especially severe in hot climates, seriously affects the energy consumption of the building [2,4].

In order to reduce heat gain in buildings, one possible strategy could be the increase of building surfaces solar reflectance during daily hours [2]. Classic highly reflective materials tend to be white or light-coloured, and therefore it is not always feasible to use them for aesthetic and architectural reasons. Therefore, the study of coloured materials, different than white, which can reflect solar radiation, has recently started to gain a lot of attention in the scientific community [5,6].

One of the typical materials used in building envelopes is ceramic tile, whose surface used to be coloured. Ink-jet printing is the generalised technique employed for the decoration of ceramic tiles [7]. Therefore, this work comprises an introductory study on the effect of different printing conditions, i.e. the printing mode (binary and grey scale) and the ink coverage, on the solar reflectance of ceramic tiles.

Moreover, the possibility of correlating the solar reflectance to the chromatic coordinates helps to optimise the design of ceramic tiles to obtain, with the available materials, the maximum solar reflectance allowed.

2. MATERIALS

Glazed porcelain tiles were chosen for the present study. Tiles were digitally printed in binary and grey scale modes. Thus, squared colour patches of 6.5 cm were printed with diverse inks (black, cyan, magenta, yellow and mixtures of these) and different percentages of coverage (from 10% to 100%) as shown in the figure below.

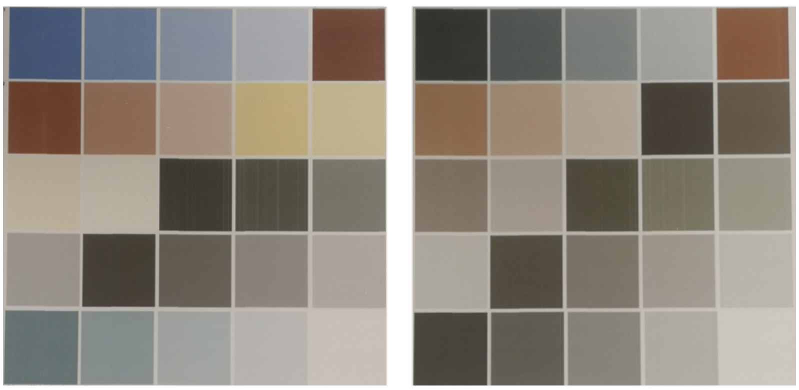

Figure 1. *Printed tiles in grey scale mode*

3. EXPERIMENTAL PROCEDURE

3.1 PREPARATION OF THE SAMPLES

The tiles were industrially printed and fired. Each printed patch was then cut from the tile using a diamond cutting blade, cleaned with ethanol, referenced and dried in an oven at 100 ºC.

3.2 DETERMINATION OF THE CHROMATICITY COORDINATES

The chromaticity coordinates were measured by means of a spectrophotometer (GretagMacbeth color–eye 7000A, X–rite) according to the ISO 10545–16 standard. To determine these coordinates, a CIE D_{65} standard illuminant was used, which represents an average daylight, and a CIE 10º 1964 standard observer. The measurements were made based on the CIELab chromaticity coordinate system.

3.3 MEASUREMENT OF SOLAR REFLECTANCE

Solar reflectance (ρ) was determined according to the ASTM C1549 standard using a reflectometer (SSR–ER, Devices & Services Company). The measurement device comprises a measurement head which contains a tungsten halogen lamp that acts as a radiation source, and four detectors, each one coupled to different colour filters to tailor its electrical response to a range of wavelengths, covering the entire spectrum of solar radiation (ultraviolet, visible and near-infrared).

The test sample was irradiated with a diffused light from the tungsten lamp, and the reflected energy was measured at an angle of incidence of 20º with respect to normal by the four detectors. Finally, with the values of each detector, a mean solar reflectance is calculated as a weighted average. Prior to the measurements, a blackbody cavity with known solar reflectance was used as a standard for the equipment calibration.

3.4 SURFACE EXAMINATION

The surface of the patches of 25% coverage was evaluated and compared using an optical microscope (BX53 M, Olympus) equipped with a colour camera (DP22, Olympus). In addition, micrographs were treated with an image analysis software (ImageJ) to analyse the distribution of grey shades.

3.5 CORRELATION BETWEEN SOLAR REFLECTANCE AND CHROMATICITY COORDINATES

The mean solar reflectance of a material depends on its behaviour over the entire solar spectrum (from the ultraviolet to the near-infrared interval). Although the behaviour at different wavelengths is not necessarily related, it remains constant for the same type of material and so it can be correlated. This relationship can be used to estimate its behaviour from simple measurements.

Traditionally, solar reflectance of tiles has been correlated with its lightness (L^*). However, the influence of colours on the reflectance of a surface is well known.

In this work, for a specific set of inks and a specific product, the relationship of the mean solar reflectance to the chromaticity coordinates has been tested, covering the entire colour space allowed by the set of inks used. For this purpose, a simple linear equation, both in the coefficients and in the variables, has been used (eq. 1).

$$\rho_{mean} = \beta_0 + \beta_1 L^* + \beta_2 a^* + \beta_3 b^* \quad \text{(eq. 1)}$$

Where ρ_{mean} is the mean solar reflectance, L^*, a^* and b^* are the chromaticity coordinates, and β_0, β_1, β_2 and β_3 are the model coefficients. All regressions have been calculated using the ordinary least square method.

Moreover, through an ANOVA statistical analysis of the results obtained with the model, it was possible to determine the correlation coefficient (R^2) and the standard error of the regression.

It is important to note that this model is empirical, and characteristic of the system studied. Therefore, any change in engobe, glaze or ink (composition and printing mode) should be considered and the model recalibrated.

4. RESULTS AND DISCUSSION

4.1 RADIANT BEHAVIOUR OF THE INKS USED

The reflectance of the printed inks was studied in three characteristic spectra: ultraviolet (UV), visible (VIS) and near-infrared (NIR). The average reflectance was calculated from the reflectance in each of these intervals, weighted by the fraction of solar energy received in each of them. Figure 2 shows the most relevant results of one of the systems studied.

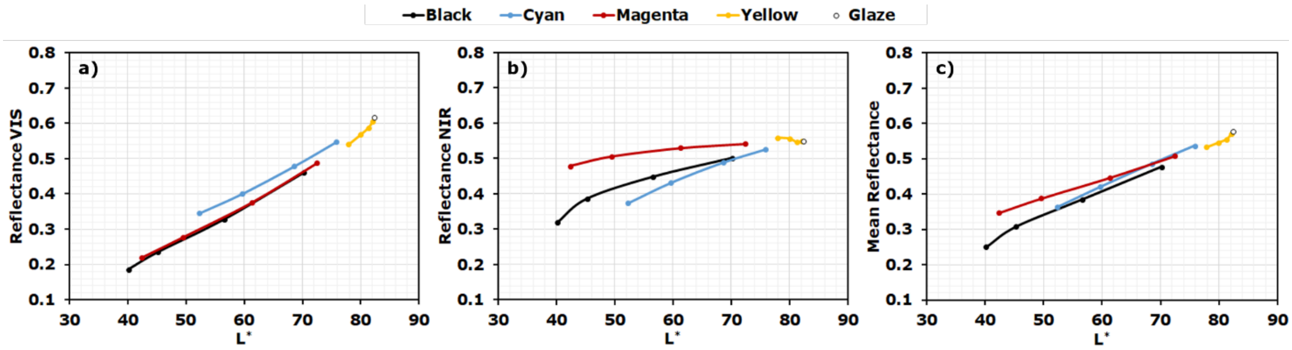

Figure 2. *Radiant behaviour of basic colours. a) Visible spectrum, b) Near-infrared spectrum, c) Mean solar reflectance*

As expected, in the visible spectrum (VIS), solar reflectance is linearly related to lightness (L^*). Nevertheless, in the near-infrared spectrum (NIR) this linear relationship is lost, especially at low L^* (high coverage), and differences between inks are more pronounced. Regarding the mean solar reflectance, the behaviour of the different inks is intermediate to that shown in each spectral region (visible and near-infrared).

In any case, the trend of the results is always the same, i.e. the yellow ink always gives the highest solar reflectance while the black ink gives the lowest values. The cyan and magenta inks give intermediate mean reflectance values, although with contrasting behaviour in the visible and infrared spectra. Magenta ink has higher reflectance than cyan in the infrared, while it is lower in the visible. The weighting of these behaviours leads to this ink having a slightly higher reflectance than cyan.

Concerning the mixtures of inks, independently of the spectrum, an intermediate behaviour can be seen between the basic colours used for each mixture. As an example, the results for the near-infrared spectrum are shown in figure 3.

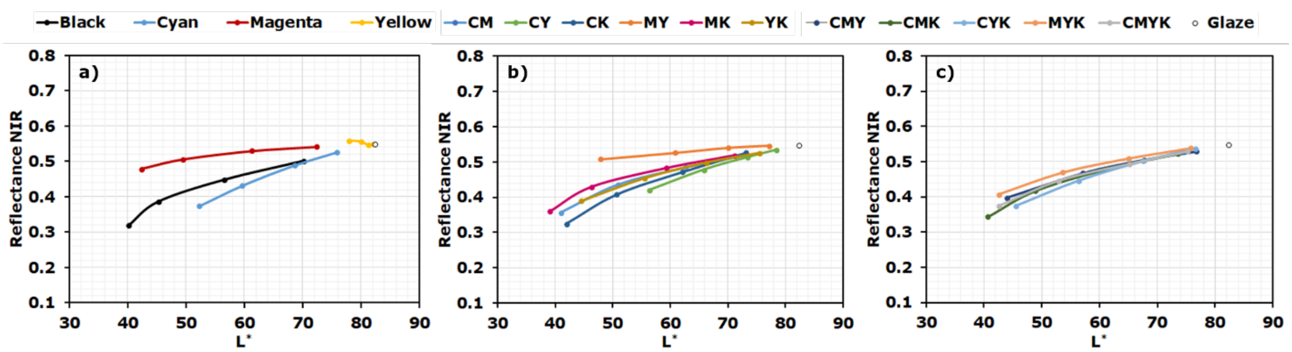

Figure 3. *Radiant behaviour in near-infrared spectrum. a) Basic colours, b) Binary mixtures, c) Ternary and quaternary mixtures*

However, for a fixed L* value, the differences between colours are less as the number of mixed inks is increased, giving rise to no difference when 3 and 4 inks are mixed.

The tiles printed in binary mode display the same trends.

4.2 EFFECT OF INK COVERAGE ON VISUAL EFFECT AND RADIATION PERFORMANCE

The effect of the percentage of ink coverage has been studied through the lightness (L*) and the mean solar reflectance. Figure 4 shows the relation between these two parameters with the percentage of coverage for the glazed porcelain tiles printed in grey scale mode.

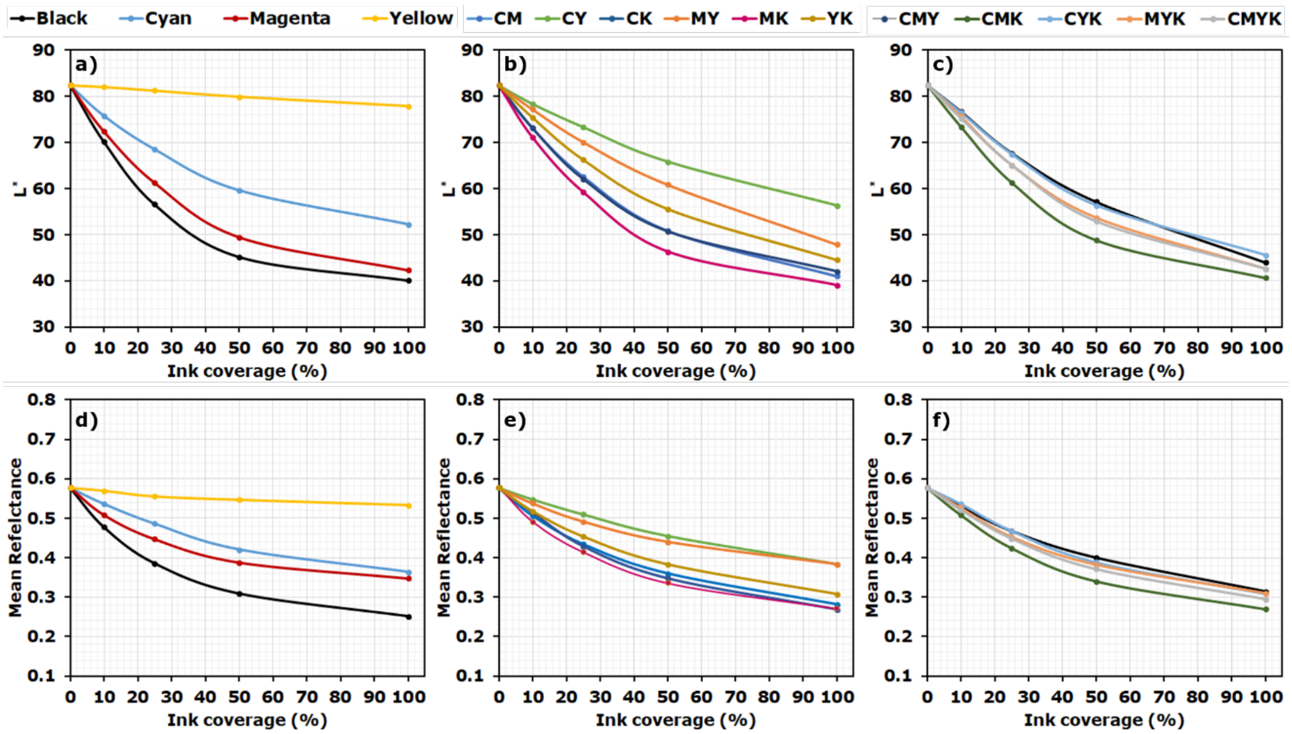

Figure 4. *Effect of ink coverage on L* (top) and mean reflectance (bottom). a) and d) Basic colours, b) and e) Binary mixtures, c) and f) Ternary and quaternary mixtures*

As it can be seen, regardless of the colour, the higher the percentage of coverage the lower the lightness. Consequently, as the mean solar reflectance is highly influenced by the lightness of the sample, this reduction in L* due to the increment of the ink coverage results in a decrease of the mean solar reflectance. When the mixtures of inks are analysed, the trends are the same, but as mentioned in the above section, the higher the number of mixed inks the less the difference between lightness and mean solar reflectance.

Concerning the tiles printed in binary mode, they display the same trend.

4.3 INFLUENCE OF THE PRINTING MODE

The effect of the printing mode (binary – grey scale) has been analysed by comparing the patches printed with 25% coverage. From the micrographs obtained by means of the optical microscope, it is possible to appreciate the different distribution of the ink drops as a function of the printing mode. As an example, the micrographs corresponding to the black and cyan inks are shown, as well as histograms of its lightness.

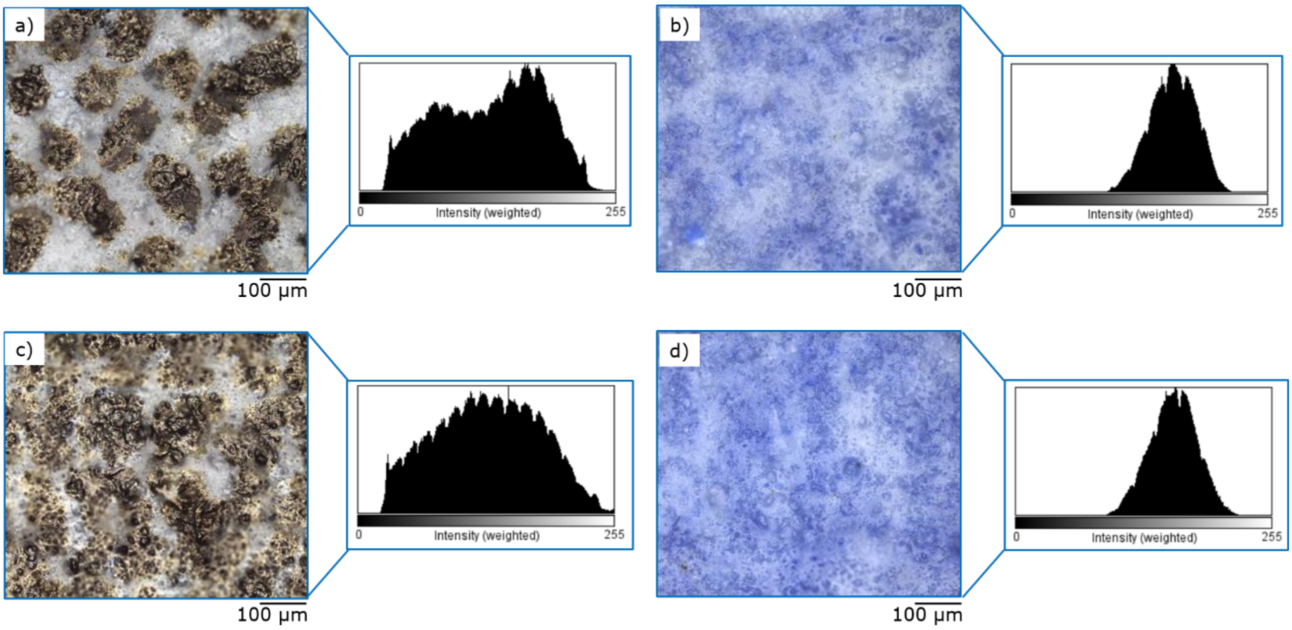

Figure 5. *Comparison of both printing modes. Binary mode: a) Black ink, b) Cyan ink. Grey scale mode: c) Black ink, d) Cyan ink*

The patch printed in binary mode with the black ink (Figure 5a) displays ink drops distributed over the entire surface in an isolated manner, thus obtaining a bimodal distribution of lightness intensity. In contrast, the distribution of ink drops for the grey–scale printed patch is more homogeneous (Figure 5c), with contact points between drops, resulting in a monomodal distribution of lightness. The magenta ink shows the same trend as black, while this difference in the distribution of ink droplets is not so easy to appreciate for cyan (Figure 5b). Even though the lightness distribution is monomodal for both printing modes, in the case of grey scale printing (Figure 5d) the distribution is narrower, so it is understood that the cyan ink drops are more homogeneously distributed on the surface. The yellow ink exhibits the same behaviour as the cyan ink.

On the other hand, for the glazed porcelain tiles printed in both modes, the mean solar reflectance as a function of L^* has been compared for the different inks and coverages. In the graphs (Figure 6) it can be seen that, for high percentages of coverage (lower L^*) of black ink there are no significant differences, while at low percentages, printing in grey scale mode (GSM) results in darker shades (lower L^*). In addition, at low percentages of coverage it is also observed that for a given value of L^*, printing in grey scale results in higher solar reflectance values.

The magenta ink displays the same trend. In the case of cyan ink, although there is no difference in solar reflectance when printing in binary or grey scale modes, it is still found that for the latter darker shades are obtained at low percentages of coverage. Again, the yellow ink displays the same behaviour as the cyan ink.

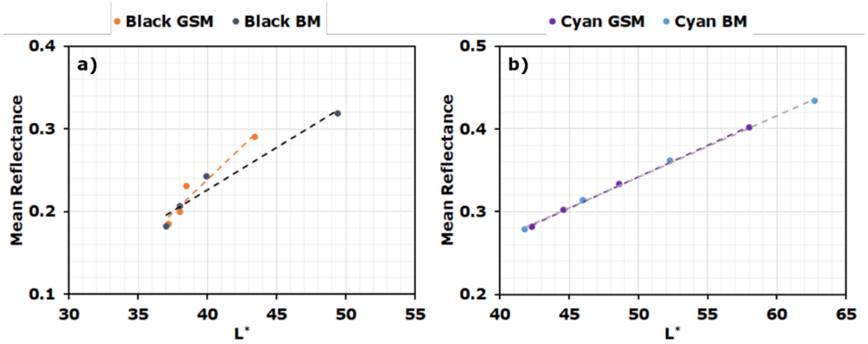

Figure 6. *Mean reflectance as a function of L* for binary mode (BM) and grey scale mode (GSM). a) Black ink, b) Cyan ink*

Therefore, the results obtained demonstrate that grey scale mode results in darker shades and, for a fixed value of lightness (L^*), a similar or higher mean solar reflectance is obtained depending on the ink used.

4.4 VALIDATION OF THE METHODOLOGY

Three different empirical models were obtained as a function of the chromaticity coordinates after the characterisation of the patches (basic colours and mixtures). The models are shown below.

$$\rho_{mean} = 0.0227 + 0.0072L^* \text{ (eq. 2)}$$

$$R^2_{adjusted} = 0.9455 \qquad Standard\ error = 0.0264$$

$$\rho_{mean} = -0.0203 + 0.0076L^* + 0.0034a^* \text{ (eq. 3)}$$

$$R^2_{adjusted} = 0.9761 \qquad Standard\ error = 0.0175$$

$$\rho_{mean} = -0.0158 + 0.0076L^* + 0.0032a^* - 0.0002b^* \text{ (eq. 4)}$$

$$R^2_{adjusted} = 0.9766 \qquad Standard\ error = 0.0173$$

From these results, it can be seen that it is possible to obtain an acceptable empirical equation which relates the mean solar reflectance to the L^* chromaticity coordinate (Equation 2), since a reasonably high R^2 value and a very small standard error are obtained.

When the reflectance values are correlated with the coordinates L^* and a^*(Equation 3), the resulting model is much better than the previous one (only with L^*), since the value of R^2 increases and the standard error is reduced a little more.

Finally, by including the b* coordinate in the model (Equation 4), no significant differences can be seen with respect to the model obtained only with L* and a*, since the values of R^2 and standard error are practically the same. Moreover, the model adjustment coefficient for the b* coordinate (β_3) is practically zero, so it hardly modifies the estimated value of the mean solar reflectance.

As a result, it can be considered that the use of the chromatic coordinates a* and b* allows improving the estimation of the reflectance of a specific system, the first of them being more significant.

Finally, in order to test the validity of the models (equations 2 to 4), they were applied to industrial tiles in which the lightness and shade had been varied. These tiles were printed in grey scale mode with the same set of inks used to print the patches employed in the development of the empirical models.

For each piece and estimation, the root-mean-square-error (RMSE) was calculated. RMSE is a useful tool to measure the accuracy of a property estimated by an equation or model. The RMSE is always non-negative and the closer it is to zero, the higher the precision of the estimation.

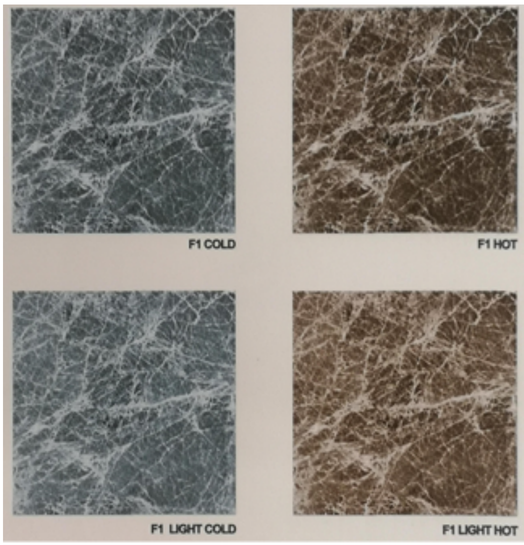

Figure 7. *Industrial tiles tested*

Concerning the industrial tiles, their L*a*b* coordinates calculated from the profiling adobe RGB file are shown in table 1.

Piece	L*	a*	b*
F1 cold	57.59	-1.19	-4.70
F1 light cold	60.90	-1.26	-5.16
F1 hot	53.52	3.59	5.29
F1 light hot	57.17	4.37	6.47

Table 1. *Chromaticity coordinates of the real ceramic tiles*

These coordinates were used in equations 2 to 4 to estimate the solar reflectance of the tiles, these estimated values being compared to the experimentally measured ones. All solar reflectance (measured and estimated) are shown in table 2.

Piece	Mean solar reflectance			
	Experimentally measured	Calculated with eq. 2	Calculated with eq. 3	Calculated with eq. 4
F1 Cold	0.43	0.44	0.41	0.42
F1 Light Cold	0.44	0.46	0.44	0.44
F1 Hot	0.41	0.41	0.40	0.40
F1 Light Hot	0.44	0.43	043	0.43
	RMSE	0.013	0.009	0.007

Table 2. *Comparison of the experimental and estimated mean solar reflectance*

From the above table, it can be seen that the three empirical equations give rise to solar reflectance values very close to those experimentally measured, and the error in the prediction (RMSE) is reduced as the different coordinates are included in the equation. Moreover, it is said that only including L^* and a^* coordinates in the empirical model is enough as no significant differences were obtained in R^2 and standard error when b^* is included. Nevertheless, after checking the RMSE, it is necessary to include the b^* coordinate in the model since the estimation is more accurate (closer to zero).

5. CONCLUSIONS

After analysing all the results obtained, the following conclusions can be drawn:

- An increase in the percentage of coverage decreases both the lightness (L^*) and the mean solar reflectance of all samples regardless of the colour and the printing mode.

- For lower percentages of coverage, darker surfaces have been obtained by printing in grey scale.
  - At equal luminosity (L^*), the mean solar reflectance of grey–scale prints is higher than in binary mode (black and magenta inks), so it would be advisable to use this system.

- For low and medium coverages, the solar reflectance depends linearly on the L^* coordinate.
  - The slope is different for each ink.

- When the coverage is high, solar reflectance decreases non-linearly as L^* is reduced.
  - The onset and magnitude of this decrease is dependent on each ink.

- It is advisable to make designs with warm colours such as magenta and yellow rather than blue as they give rise to higher solar reflectance.

- It is possible to obtain an empirical model, with an acceptable standard error and high accuracy, that allows the mean solar reflectance to be estimated as a function of chromaticity coordinates $L^*a^*b^*$.
  - The calibration chart used to develop the model must include at least:
    - Basic colours and binary mixtures.
    - At least 6 different percentages of coverage.
    - Ink linearization.
  - The model is independent of printing issues, as it depends on chromaticity coordinates $L^*a^*b^*$.
  - The model depends on the materials used (body, engobe and glaze) as the used inks are not opaque, as well as on the firing conditions.
  - It would be possible to include the empirical equation in the design process to estimate the behaviour of any design regarding mean solar.

6. REFERENCES

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