ADAPTATION OF CERAMIC TILE DIMENSIONAL TOLERANCES TO PRODUCT TYPE AND PROCESSING CONDITIONS

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ABSTRACT

This paper puts forward a method of calculating dimensional tolerances for ceramic tiles, with a view to adapting product quality standards to the real capabilities of the available manufacturing processes and control systems.

The results enable new tolerances, which are less constraining than the current ones, particularly for large sizes, to be proposed. The proposed tolerances can be attained with the available production means and are always much lower than the requirements laid down in the applicable standards.

1. INTRODUCTION

One of the most important parameters conditioning ceramic tile quality is tile dimensional stability. In regard to dimensional stability, tiles are classified according to two characteristics: differences in the dimensions of the same tile (wedging or departures from rectangularity) and differences in the overall dimensions between tiles (calibres). The tolerances used in tile manufacturing processes in Spain to detect dimensional stability problems are the tolerances demanded by the market itself, as the tolerances laid down in the applicable standards (ISO 13006 and EN 14411, currently the same[1,2]) are not very restrictive, as this study will show.

Despite the importance of dimensional tolerances within the set of properties that determine end-product quality, it has been observed that, in most cases, they do not match either the type of product or the actual operating conditions. Indeed, on the one hand, the tolerances defined by the reference standards with relation to the levels of quality targeted at present are not very demanding. On the other, market demands have become so restrictive, particularly in large-sized products, that they cannot be achieved with current production means.

New dimensional tolerances, adapted both to market demands and to the constraints of current production means, therefore need to be established. For this purpose, in this study, an equation is used that allows tile end size to be related to the main variables of the different manufacturing process stages. This relationship, obtained in a previous study[3], takes into account the dimensional changes that the tile undergoes during the manufacturing process, as schematically illustrated in Figure 1.

As may be observed in Figure 1, ceramic tiles undergo dimensional changes during the different manufacturing process stages. Stage 0 corresponds to die filling in the press with the spray-dried powder. In this stage, the dimensions (thickness, h, and diameter or length, X) refer to the press die volume (h_0 and X_0). In stage 1, pressing, the spray-dried powder is compacted, powder bed volume decreases, and the dimensions of the body correspond to h_1 and X_1, where $X_1=X_0$. After pressing, stage 2, the tile expands, known as after-pressing expansion. Finally, in stages 3 and 4, drying and firing respectively, different types of tile shrinkage take place, known as drying and firing shrinkage.

Figure 1 also shows the different variables to be taken into account in order to analyse the volume changes that occur in the ceramic bodies in the course of the tile manufacturing stages.

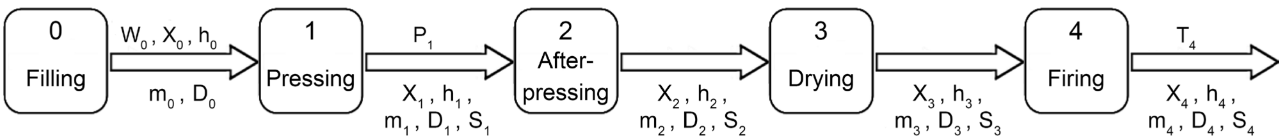

Figure 1. Flow chart and variables of the ceramic tile manufacturing process.

The process variables are as follows:

W_0: Moisture content on a dry basis (%)

X: Dimension (mm): on a laboratory scale, this corresponds to the diameter of a cylindrical test piece; on an industrial scale, to the width or length of the tiles.

h: Thickness (mm)

m: Mass (g)

D: Bulk density (kg/m^3)

P_1: Maximum compaction pressure (MPa)

S: Linear dimensional change based on length or diameter (%)

T_4: Peak firing temperature (°C)

The subscripts represent the sequential unit operation to which they belong. The variables shown above the arrows of the flow chart in Figure 1 are so-called independent variables, which have fixed values, whereas the variables shown below these arrows are dependent variables, whose values are estimated.

To calculate tile end size (X_4), in accordance with Figure 1, it is necessary to take into account variables S_2, S_3, and S_4, corresponding to the dimensional changes that develop in the tile. These variables are calculated as a percentage, in the following form:

Eq. 1 $S_i=100(X_{i-1}-X_i)/X_{i-1}$

Assuming that, after pressing and before extraction from the press die, the length or diameter of the body (X_1) is the same as the dimension of the die (X_0) and that the after-pressing expansion (S_2) and the drying and firing shrinkages (S_3 and S_4) are independent of the direction, the equation for calculating the size of the body after firing (X_4) may be written as:

Eq. 2 $X_4=(100-S_2)(100-S_3)(100-S_4)10^{-6}X_0$

For a given composition, after-pressing expansion (S_2) and drying shrinkage (S_3) basically depend on powder moisture content (W_0) and maximum compaction pressure (P_1). Firing shrinkage (S_4) is mainly a function of the bulk density after drying or dry bulk density (D_3) and peak firing temperature (T_4). In turn, D_3 depends on W_0 and P_1. Thus, S_2, S_3, S_4, and D_3 can be calculated for a particular composition from independent variables W_0, P_1, and T_4 using Eqs. 3 to 6.

Eq. 3 $S_2=f\ (W_0,P_1)$

Eq. 4 $S_3=f\ (W_0,P_1)$

Eq. 5 $S_4=f\ (D_3,T_4)$

Eq. 6 $D_3=f\ (W_0,P_1)$

Dry bulk density (D_3) is customarily used to control the ceramic tile manufacturing process[4] and tile end characteristics, mainly tile size (X_4). However, as may be deduced from Eqs. 2 to 5, tile end size does not solely depend on D_3 but is also a function of P_1, W_0, and T_4.

Eq. 7 $X_4=f\ (P_1,\ W_0,\ D_3,\ T_4)$

Tolerance is defined as the maximum allowable difference between the dimensions of a tile (wedging) or of two different tiles (calibre), before there is deemed to be a problem of dimensional stability. For the sake of simplicity, the proposed approach will be used for the case of calibre, though the approach and the conclusions are equally valid for wedging. Tolerance (t) in calibre will thus be defined as:

Eq. 8 $$t = X^{*}_{4} - X^{*}_{4} = \Delta X_{4}^{*}$$

and can be obtained by differential calculation from Eq. 2.

1.1. CALCULATION OF THE MAXIMUM ALLOWABLE VARIATION FOR DRY BULK DENSITY (ΔD_3^*) AND THE MINIMUM TOLERANCE (t_*)

Applying the differential calculation to Eq. 2 yields Eq. 9.

Eq. 9 $$dX_4 = \left.\frac{\partial X_4}{\partial S_2}\right|_{S_3S_4} dS_2 + \left.\frac{\partial X_4}{\partial S_3}\right|_{S_2S_4} dS_3 + \left.\frac{\partial X_4}{\partial S_4}\right|_{S_2S_3} dS_4$$

In order to solve Eq. 9 analytically, Eqs. 3 to 6 must be known. Previous studies[5,6,7] have shown that dry bulk density (D_3) depends on press powder moisture content (W_0) and on maximum pressing pressure (P_1) in accordance with a semi-logarithmic equation; after-pressing expansion (S_2) and drying shrinkage (S_3) depend linearly on press powder moisture content (W_0), the ordinate moreover being at the origin and the slope of these equations being linear functions of maximum compaction pressure (P_1). Firing shrinkage (S_4) also depends linearly on dry bulk density (D_3), the coefficients of this correlation depending on peak firing temperature (T_4). Eqs. 3 to 6 thus remain in the form:

Eq. 10 $$S_2 = (aP_1 + b)W_0 + (cP_1 + d)$$

Eq. 11 $$S_3 = (eP_1 + f)W_0 + (gP_1 + j)$$

Eq. 12 $$S_4 = (kT_4^2 + lT_4 + n)D_3 + qT_4^2 + rT_4 + u$$

Eq. 13 $$D_3 = vW_0^x \ln(P_1) + yW_0^z$$

1.1.1. Calculation of the maximum allowable variation for dry bulk density (ΔD_3^*) and the minimum tolerance (t_*) assuming S_2 and S_3 to be constant

In accordance with the literature surveyed, the values of S_2 and S_3 are much smaller than those of S_4[7,8]. Consequently, in all studies performed to date[4,9], only the effect of the variation of S_4 on tile end size has been considered. In accordance with these considerations, and taking into account Eqs. 2 to 5 and Eq. 12, and converting the differential elements into incremental maximums, Eq. 8 then takes on the form:

Eq. 14 $$\Delta D_3^* = \frac{t(100 - S_4) - \left|(2kT_4 + l)D_3 + 2qT_4 + r\right| \Delta T_4^* X_4}{X_4 \left|kT_4^2 + lT_4 + n\right|}$$

This equation is identical to the equation obtained under the same conditions by other researchers[9], and it indicates that ΔD^*_3 depends on X_4, t, D_3, S_4, and T_4 and its maximum variation (ΔT_4^*). The values of T_4 and S_4 are highly conditioned by product type, as they determine product water absorption; in addition, for a given installation, the values of D_3 and, particularly those of ΔT_4^*, are usually constant. It may therefore be considered that ΔD^*_3 will essentially depend on the tolerance value (t) and on tile end size (X_4).

In accordance with this equation, there is a minimum tolerance (t_*), defined as the tolerance when the maximum variation of dry bulk density (ΔD^*_3) is equal to twice the absolute error of the dry bulk density measurement method (p). The smallest tolerance size that can be demanded of the manufacturing process is the minimum tolerance (t_*), as smaller tolerances would require more precise bulk density measurement methods. If the tolerance used in industrial practice (ti) is smaller than the minimum tolerance ($t_i<t_*$), it is technically impossible to produce tiles of the same size without calibres or wedging. Consequently, the value of the tolerance used in industrial practice (t_i) must be larger than or equal to the minimum tolerance (t_*).

In accordance with these premises, the minimum tolerance (t_*) may be calculated from the following expression:

Eq. 15 $$t_* = -\frac{X_4}{(100-S_4)}\left[\left|kT_4^2 + lT_4 + n\right|p + \left|(2kT_4 + l)D_3 + 2qT_4 + r\right|\Delta T_4^*\right]$$

For a given product (constant T_4 and S_4), manufacturing process (constant D_3 and ΔT_4^*), and bulk density measurement method ($\Delta D_3^* = p$), the minimum tolerance will depend on tile end size (X_4) in accordance with Eq. 15.

In this equation, the value of X_4 for which $t^* = t_i$ determines the maximum attainable tile size (X_4^*) for a given tolerance (t_i).

1.1.2. Calculation of the maximum allowable variation for dry bulk density (ΔD_3^*) and the minimum tolerance (t_*) assuming S_2 and S_3 to be variable

In all previously published studies, the values of S_2 and S_3 have been assumed constant. However, it has been observed that both depend on maximum pressing pressure (P_3) and on spray-dried powder moisture content (W_0). In order to consider the effect of these variables on tile end size and process tolerance, all the terms of Eq. 9 must be taken into account.

To obtain the expression of dS_2 and of dS_3, Eqs. 3 and 4 must be considered. Taking into account furthermore that the hydraulic presses used to compact the press powder have a degree of control that assures the value of the pressure setting with sufficient precision ($dP_1=0$):

Eq. 16 $$dS_2 = \left.\frac{\partial S_2}{\partial W_0}\right|_{P_1} dW_0$$

Eq. 17 $$dS_3 = \left.\frac{\partial S_3}{\partial W_0}\right|_{P_1} dW_0$$

From Eq. 6, assuming that $dP_1=0$, one can obtain the value of dW_0:

Eq. 18 $$dW_0 = \left.\frac{\partial W_0}{\partial D_3}\right|_{P_1} dD_3$$

Taking into account furthermore Eq. 5, one obtains the following expression for dS_4:

Eq. 19 $$dS_4 = \left.\frac{\partial S_4}{\partial D_3}\right|_{T_4} dD_3 + \left.\frac{\partial S_4}{\partial T_4}\right|_{D_3} dT_4$$

Substituting Eq. 18 in Eqs. 16 and 17, and the resultant equations together with Eq. 19 in Eq. 9, converting the differential elements into incremental maximums, setting $\Delta X_4^* = t$ and clearing ΔD_3^*, one obtains:

Eq. 20 $$\Delta D_3^* = \frac{t - \left|\left.\frac{\partial X_4}{\partial S_4}\right|_{S_2S_3} \left.\frac{\partial S_4}{\partial T_4}\right|_{D_3}\right| \Delta T_4^*}{\left|\left.\frac{\partial X_4}{\partial S_2}\right|_{S_3S_4} \left.\frac{\partial S_2}{\partial W_0}\right|_{P_1} \left.\frac{\partial W_0}{\partial D_3}\right|_{P_1} + \left.\frac{\partial X_4}{\partial S_3}\right|_{S_2S_4} \left.\frac{\partial S_3}{\partial W_0}\right|_{P_1} \left.\frac{\partial W_0}{\partial D_3}\right|_{P_1} + \left.\frac{\partial X_4}{\partial S_4}\right|_{S_2S_3} \left.\frac{\partial S_4}{\partial D_3}\right|_{T_4}\right|}$$

Taking into account that Eq. 2 can be written in the generic form:

Eq. 21 $$\left.\frac{\partial X_4}{\partial S_n}\right|_{Si} = \frac{-X_4}{(100 - S_n)}$$

Considering Eqs. 10 and 11:

Eq. 22 $$\left.\frac{\partial S_2}{\partial W_0}\right|_{P_1} = aP_1 + b$$

Eq. 23 $$\left.\frac{\partial S_3}{\partial W_0}\right|_{P_1} = eP_1 + f$$

Taking into account the powder compaction diagram Eq. 13:

Eq. 24 $$\left.\frac{\partial W_0}{\partial D_3}\right|_{P_1} = \frac{W_0}{vxW_0^x \ln(P_1) + yzW_0^z}$$

And finally, considering Eq. 12

Eq. 25 $$\left.\frac{\partial S_4}{\partial T_4}\right|_{D_3} = (2kT_4 + l)D_3 + 2qT_4 + r$$

Eq. 26 $$\left.\frac{\partial S_4}{\partial D_3}\right|_{T_4} = kT_4^2 + lT_4 + n$$

Substituting Eqs. 21 to 26 in Eq. 20 and grouping terms one obtains:

Eq. 27
$$\Delta D_3^* = \frac{t(100-S_4) - X_4 \Delta T_4^* \left|(2kT_4 + l)D_3 + 2qT_4 + r\right|}{X_4(100-S_4)\left\|\left[\left(\frac{W_0}{vxW_0^x \ln(P_1) + yzW_0^z}\right)\left(\frac{(aP_1+b)}{(100-S_2)} + \frac{(eP_1+f)}{(100-S_3)}\right) + \frac{kT_4^2 + lT_4 + n}{(100-S_4)}\right]\right\|}$$

This equation, similar to Eq. 14, allows calculation of the maximum variation of bulk density (ΔD_3^*), taking into account the variation of after-pressing expansion (S_2) and of drying shrinkage (S_3) with the pressing conditions (W_0 and P_1), in addition to the variation of firing shrinkage (S_4).

Taking into account the comments made in the previous section corresponding to the minimum tolerance, t_*, in this case as well, if in Eq. 27 one sets ΔD^*_3 = p, the value of the minimum tolerance can be calculated from the following equation:

Eq. 28
$$t_* = pX_4\left\|\left[\left(\frac{W_0}{vxW_0^x \ln(P_1) + yzW_0^z}\right)\left(\frac{(aP_1+b)}{(100-S_2)} + \frac{(eP_1+f)}{(100-S_3)}\right) + \frac{kT_4^2 + lT_4 + n}{(100-S_4)}\right]\right\| + \frac{X_4 \Delta T_4^* \left|(2kT_4 + l)D_3 + 2qT_4 + r\right|}{(100-S_4)}$$

2. OBJETIVE

The objectives of this study were as follows:

- To obtain an equation that allowed the minimum tolerances (t_*) for any ceramic tile composition to be calculated and to apply the equation to a porcelain tile composition.

- To propose a calculation method of industrial tolerances that allowed tiles of the same size to be obtained and to apply the method to a porcelain tile composition.

3. MATERIALS AND METHODOLOGY

A spray-dried powder composition of the type customarily used for porcelain tile manufacture was used to conduct the study. Laboratory-scale experiments were performed with a view to finding regression equations that related dry bulk density (D_3), after-pressing expansion (S_2), drying shrinkage (S_3), and firing shrinkage (S_4) of the composition to the independent variables W_0, P_1, and T_4 (Eqs. 10 to 13).

The sample preparation process consisted of preparing the press powder at different moisture contents (3,1, 4,6, 5,7, and 7,2%) and then pressing cylindrical test pieces at different maximum pressures (16,61, 29,42, 39,23, and 49,03 MPa) using a cylindrical die, 40 mm in diameter. For each pair of values W_0–P_1, four test pieces were prepared. After the test pieces had been pressed, their after-pressing expansion was determined

(S_2) and, after drying in a laboratory oven for at least 2 hours at 110ºC, their drying shrinkage (S_3) and dry bulk density (D_3) were determined. They were then fired in an electric laboratory kiln at different peak firing temperatures (1150, 1175, 1200, and 1220ºC), and the resulting test piece firing shrinkage (S_4) and external porosity, as water absorption capacity, were determined. The methods used to perform the experiments and the determination of the different parameters are described elsewhere[10].

4. RESULTADOS EXPERIMENTALES

4.1. OBTAINMENT OF THE CONSTITUTIVE EQUATIONS

- This section sets out Eqs. 10 to 13, obtained in accordance with the methodology described in the previous section, for the porcelain tile composition.

- After-pressing expansion:

Eq. 29 $$-S_2=(-3.999\cdot10^{-4}P_1 - 0.04025)W_0 + 4.926\cdot10^{-3} P_1 + 1.244$$

- Drying shrinkage: On a laboratory level, the contribution of drying shrinkage, S_3, could not be determined from the measurement of the dimensions of the test pieces, owing to the small magnitude of this variable.

- Compaction diagram:

Eq. 30 $$D_3=174.85\ W_0^{-0.1362}\cdot \ln P_1 + 1219.2\ W_0^{0.10188}$$

- Linear firing shrinkage:

Eq. 31 $$S_4=(3.94\cdot10^{-7}T_4^{2} - 1.08\cdot10^{-3}T_4+0.71)\ D_3 - 1.45\cdot10^{-3}T_4^{2} + 3.71T_4 - 2334.5$$

4.2. CALCULATION OF THE MINIMUM TOLERANCE (t_*)

The minimum tolerance was calculated using Eq. 15 and Eq. 28 for standard manufacturing conditions. Consequently, pressing pressure (P_1) and spray-dried powder moisture content (W_0) were fixed at 44.1 MPa and 6%, respectively. The peak firing temperature (T_4) at which water absorption of the composition minimised (<0.1%) was established: T_4 was found to be 1190ºC and the temperature variation in the firing zone (ΔT^*_4) was determined to be 10ºC. In accordance with the literature surveyed[11], the most precise method at present for determining ceramic tile dry bulk density is by mercury displacement, with an absolute error of ± 4 kg/m^3, so that a value of p = 8 kg/m^3 was assumed.

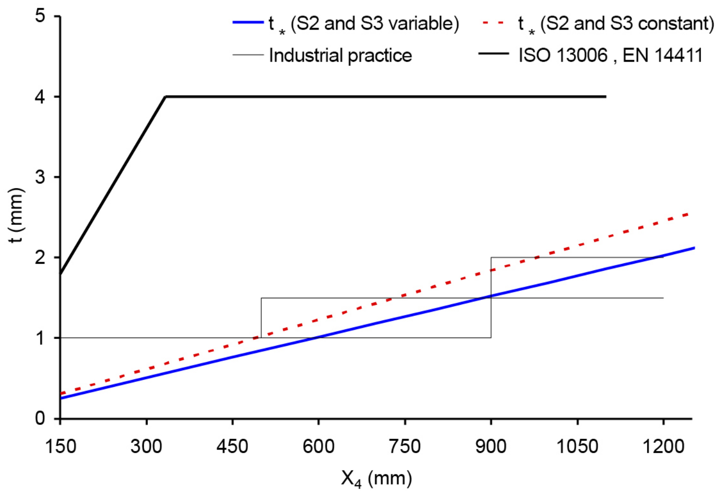

Figure 2. Variation of tolerance with tile size.

Figure 2 shows, at the working conditions set in the previous paragraph, the variation of minimum tolerance with tile size, assuming S_2 and S_3 to be constant (Eq. 15), plotted in a red dashed line, and that of the same variable when S_2 and S_3 were variable (Eq. 27), plotted in a continuous blue line. In both cases, the minimum tolerance increased with tile size, reflecting the difficulty of processing large tiles. The relationship between the tolerance and tile end size was linear and of positive slope, whereas the slope corresponding to the calculation assuming S_2 and S_3 to be constant (red dashed line) was greater. This behaviour reflects that, if S_2 and S_3 are assumed to be constant, the manufacturing process is more restrictive, which could be because the after-pressing expansion (of the order of 1% in this type of composition) partly offsets the dimensional change that the tile undergoes during firing. This fact is taken into account when S_2 and S_3 are variable; however, it is not taken into account when S_2 and S_3 are deemed constant.

In accordance with the results obtained, the minimum tolerance cannot be considered constant and will depend on the working conditions in each case. For the working conditions assumed in this section (W_0= 6,0%, P_1 = 44.10 MPa, and T_4= 1190ºC) and setting p = 8 kg/m³, the minimum tolerance can be calculated for each value of X_4 from the following expression:

Eq. 32 $$t_* = X_4 10^{-4}(8.66 + 0.83 * \Delta T_4^*)$$

Eq. 32 indicates that, at certain operating conditions (W_0, P_1, and T_4), from a technical viewpoint, the attainable minimum tolerance for a tile is a linear function of tile end size (X_4), which passes through the origin of the ordinates and whose slope depends on kiln operating conditions ($\Delta T_4{}^*$).

Figure 2 also shows the tolerance required by the standard currently in force (ISO 13006:2012 and EN 14411:2013), plotted in a bold continuous black line. It may be observed that, for all sizes, the calculated minimum tolerances are much smaller than those laid down in the standard.

In addition, Figure 2 shows the tolerances customarily used in industrial practice, plotted as continuous black lines. In order to establish these values, the criteria used in numerous Spanish ceramic sector companies have been taken into account. Most Spanish companies use tolerances of 1.00 mm for tiles with an end size below 500 mm. When tile sizes are larger (between 500 and 900 mm), some companies raise the tolerance to 1.50 mm, though most keep it at 1.00 mm. Consequently, a margin of variation between 1.00 and 1.50 mm has been assumed for the tolerance in tiles between 500 and 900 mm. For larger tile sizes (X_4>900 mm), tolerances greater than 1.50 mm are always used.

The comparison of these lines with the line corresponding to the calculated minimum tolerance assuming S_2 and S_3 to be variable is of great industrial interest. For tile sizes smaller than 600 mm, the tolerance used in industrial practice (1 mm) is greater than the minimum tolerance, which means that it is technically possible to obtain tiles with the same calibre. Above 600 mm, if a tolerance of 1 mm is used in industrial practice, this is below the minimum, it being impossible to fabricate tiles of the same size. There are a growing number of companies that, starting at values close to 600 mm, choose to increase the calibre tolerance. Identical behaviour is observed above 900 mm, if the industrial tolerance is held at 1.5 mm.

4.3. PROPOSED NEW TOLERANCES ON AN INDUSTRIAL SCALE (t_i)

The findings of the previous section indicate that the industrial tolerances need redefining, if tiles of the same calibre are to be obtained.

To calculate the tolerance on an industrial scale, it is necessary to set a value of ΔD_3^* that is greater than the measurement method error (± 4 kg/m³), that is technically attainable, and that generates tolerances close to those used at present. In order to propose new industrial calibre tolerances that meet these requirements, a value of ΔD_3^* 50% greater than the value of p, i.e. 12 kg/m³, has been assumed.

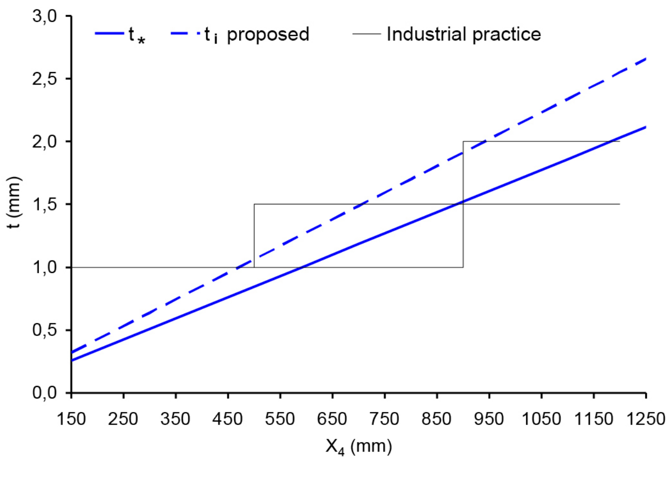

Figure 3. Proposed industrial tolerances.

Applying these criteria, using Eq. 28 for the manufacturing conditions described in section 4.2, the variation of the industrial tolerance (t_i) with tile end size (X_4) has been plotted in a blue dashed line in Figure 3. The proposed industrial tolerances (t_i), for any tile size, are obviously greater than the minimum tolerances (t_*), as they have been calculated for a considerably greater value of ΔD_3^* and, in addition, they are close to those used at present (continuous black lines) and are smaller for certain tile size ranges.

For the porcelain tile composition used and the working conditions considered (W_0=6.0%, P_1= 44.10 MPa, T_4=1190ºC, ΔT_4^*=10 ºC, ΔD_3^*=12 kg/m³), the industrial tolerance (t_i) can be calculated for each tile size (X_4) from the following equation.

Eq. 33 $$t_i = 21.24 \ 10^{-4} X_4$$

From an industrial viewpoint, it may be more practical to work with constant tolerance values for different size ranges, rather than calculate the tolerance value for each size in accordance with Eq. 33. Those tolerances, taking into account the criterion set out above and the results shown in Figure 3, are proposed in Table 1, in which the proposed tolerances are detailed together with current tolerances.

X_4 (mm)	$t_{i\ \text{(current values)}}$ (mm)	$t_{i\ \text{(proposed values)}}$ (mm)
< 450	1.0	1.0
450-700	1.0-1.5	1.5
700-900	1.0-1.5	2.0
900-1150	1.5-2.0	2.5

Table 1. Proposed industrial tolerances.

5. CONCLUSIONS

The study allows the following conclusions to be drawn:

- There is a minimum tolerance for tile size (t_*) below which it is technically impossible to obtain ceramic tiles without dimensional stability problems. The tolerance used in industrial practice (t_i) needs to be greater than the minimum tolerance ($t_i > t_*$).

- For the studied composition, it is technically impossible to obtain tiles that have the same size when they are larger than 600 mm, if a tolerance of 1 mm is maintained.

- The existence of a minimum tolerance is basically determined by the precision of the bulk density measurement method. When the precision of the measurement method is increased, the minimum tolerance decreases, enabling tiles to be obtained with greater dimensional stability. The minimum tolerance also depends on tile end size (X_4), on the operating conditions (W_0, P_1, T_4, and ΔT_4^*), and on press powder behaviour during powder processing (D_3, S_2, S_3, and S_4).

- For the same press powder composition and defined operating conditions, the minimum tolerance for tile size is a linear function of tile end size, and it increases as tile size increases. Therefore, the industrial tolerance needs to be modified as a function of tile end size.

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