# MODELLING AND NUMERICAL SIMULATION OF CERAMIC TILE LINEAR SHRINKAGE FROM THE FIRING CURVE

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## 1. INTRODUCTION

Ceramic tile production by the single-firing process is currently the most widespread manufacturing approach. Research into firing in this process is of great importance for the ceramic industry, as the industry needs to adapt to the new parameters of productivity, quality, and energy efficiency due to technological growth and product diversification. The literature shows that numerical simulation can be successfully used in these cases. In this study, a phenomenological model based on heat transport by conduction was applied to determine the evolution of the temperature profile in the ceramic slab during heating, using a kinetic sintering model to determine linear shrinkage. These data allowed the final dimensions of a class BIIa, red-body ceramic stoneware tile to be determined.

## 2. EXPERIMENTAL PROCEDURE

The model was obtained from the phenomenon of heat transfer by conduction in a ceramic tile, disregarding the effects caused by the chemical reactions that occurred in the body, in accordance with equation (1). The modelling on energy conservation in the ceramic tile, which describes the variation of temperature as a function of time and position (BIRD, 2002), was used. At the beginning of the process, the temperature of the entire ceramic tile is equal to ambient temperature, this being considered the initial condition of the problem. The convection and radiation phenomena at the surface are considered one of the boundary conditions at the top and bottom surfaces. In the centre of the tile, the symmetry condition was considered.

$$\rho c_p \frac{\partial T}{\partial t} = -\left(\frac{\partial q"_{cd,x}}{\partial x} + \frac{\partial q"_{cd,y}}{\partial y} + \frac{\partial q"_{cd,z}}{\partial z}\right) \qquad (1)$$

Equation discretisation and the boundary conditions were performed using the finite volume method with the CDS interpolation function (Maliska, 2004). In addition to obtaining the equation of the temperature profile, sintering was also examined by the kinetic model used by Orts *et al*. (1993), Benavidez and Oliver (2001) and Salem *et al*. (2009) for ceramic material, in accordance with equation (2).

$$R_l = k_0 \cdot e^{\left(\frac{-E_A}{R \cdot T}\right)} \cdot t^n \qquad (2)$$

where "$R_l$" is linear shrinkage of the ceramic tile, "$k_0$" the frequency factor, "$E_A$" activation energy, "R" the ideal gas constant, "T" ceramic tile temperature, "t" sintering time at the end of the firing zone, and "n" the exponent of time that depends on the predominant sintering mechanism (KINGERY, 1975). The parameters "$k_0$", "$E_A$", and "n" were determined from the experimental shrinkage data by linearising equation (2) and least squares fitting, after firing test pieces measuring 80x20x2,3 $mm^3$ (1,847 g/cm³, dry bulk density), fired in a laboratory roller kiln under different conditions: 30, 40, and 50 min (cold-to-cold) and maximum temperatures ranging from 1273 K to 1423 K (increments of 30 K).

This model was applied to the industrial firing of an unglazed product measuring 450x450x80 $mm^3$, 30 min firing cycle (cold-to-cold), and peak temperature of 1425 K. The experimental data were compared with those obtained with the model.

## 3. RESULTS AND DISCUSSION

The following kinetic sintering parameters were determined: $E_A$ = 178000 J/mol, n = 0,26280, $k_0$ = 44770 $s^{-1}$. The experimental linear shrinkage values at firing times of 30, 40, and 50 minutes and temperature of 1393 K were 0,0590, 0,0638, and 0,0681, respectively. The firing curves in the laboratory kiln are plotted in Figure (1). These values correspond approximately to the simulated values of 0,0599, 0,0647, and 0,0687. Figure (2) shows the linear shrinkage values for all conditions. It demonstrates the capability of the model to simulate linear firing shrinkage from 0,01 to 0,07.

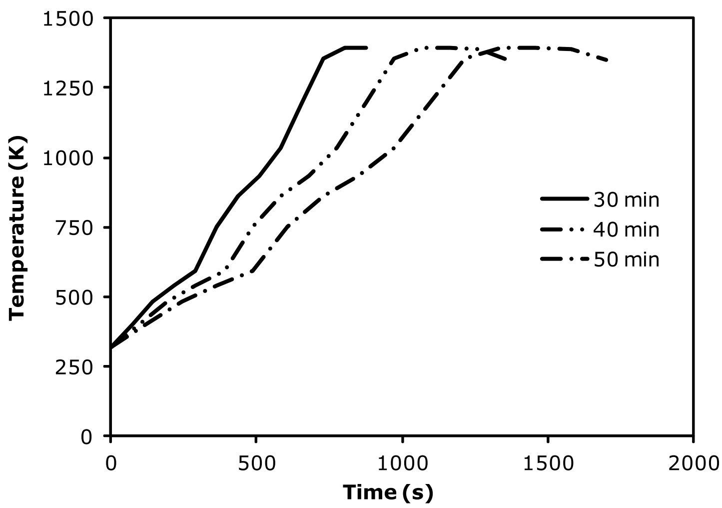


*Figure 1 – Firing curves in the laboratory kiln for different firing times at a temperature of 1120°C.*

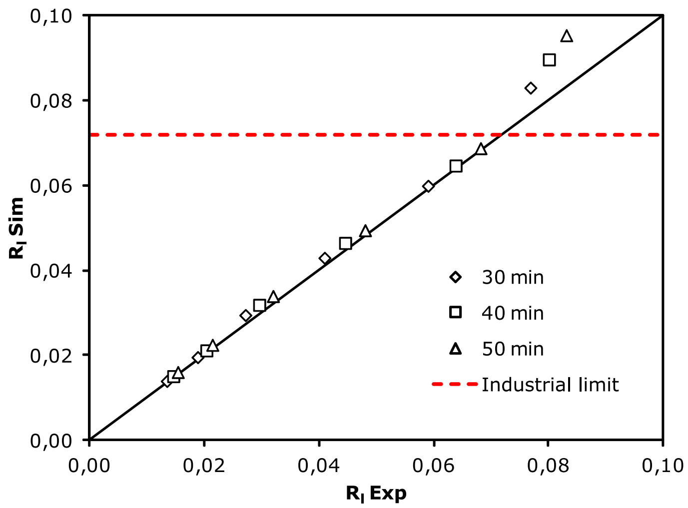


*Figure 2 - Comparison of the experimental data ($R_l$ Exp) and simulated values ($R_l$ Sim) of ceramic tile firing at different firing times ($R^2$ = 0,9913).*

Figure (3) depicts the result of the temperature profile and the hypothetical linear shrinkage profile of the ceramic tile fired under industrial conditions. It may be observed that there is a wide variation in temperature and linear shrinkage between the surface and the centre of the ceramic tile at the end of the firing zone. In order to determine ceramic tile linear shrinkage, the average temperature was first established by integrating the temperature profile, as shown in Equation (3). With the average temperature, the position in the thickness of the tile and the corresponding linear shrinkage value were determined. In this case, the average temperature value of the ceramic tile was 1407 K. This is the temperature that corresponds to a distance of +/-2,3 mm from the centre of the slab. At this point, the simulated shrinkage and, therefore, tile shrinkage were assigned a value of 0,0663. As the initial size was 481,38 mm, the simulated final size was 449,46 mm.

$$\bar{T}_{\text{slab}} = \frac{1}{z}\int T(z)dz \qquad (3)$$

Where "T" is the average temperature of the slab, "z" is thickness, and T(z) is the temperature profile function.

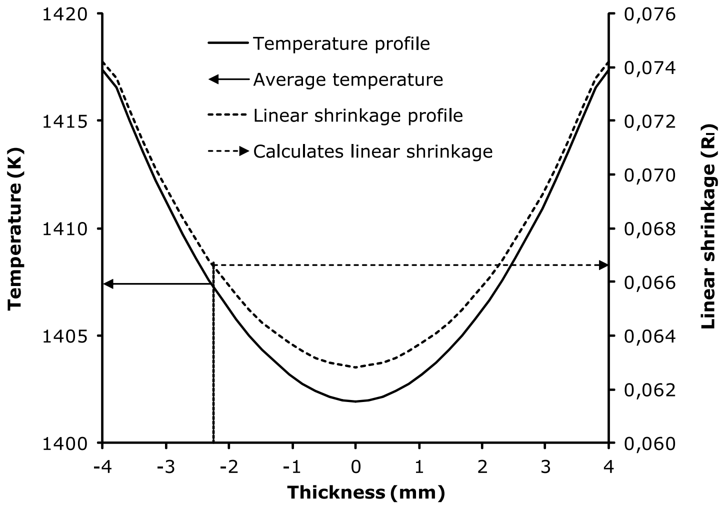


*Figure 3 - Temperature profile and hypothetical linear shrinkage as a function of tile thickness.*

The experimental result for shrinkage was 0,0664 and 449,41mm, -0,05mm of the numerically obtained shrinkage. Figure (4) presents a comparison of the experimental linear shrinkage ($R_l$ Exp) and the simulated linear shrinkage ($R_l$ Sim). The numerical results obtained for linear shrinkage display a relative error of 0,15% compared with the experimental data. The model was able to reproduce the experimental data with great accuracy.

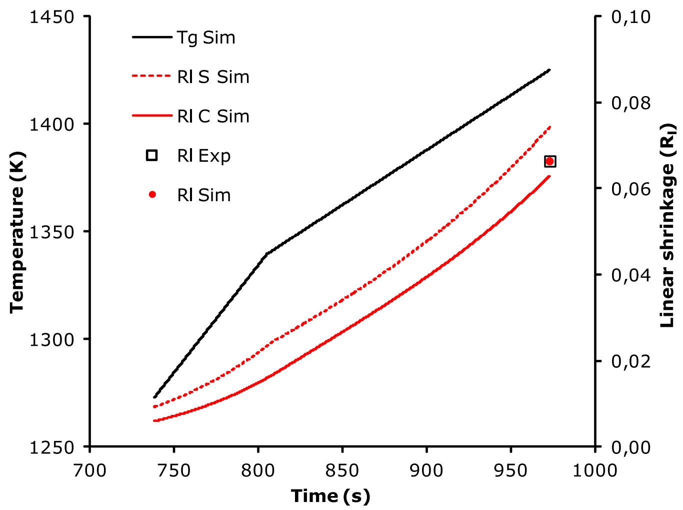


*Figure 4 - Comparison of the simulated linear shrinkage at the surface ($R_l$ S = 0,0742), at the centre ($R_l$ C = 0,0628), the average simulated ($R_l$ Sim = 0,0663) and experimental shrinkage ($R_l$ Exp = 0,0664) obtained industrially. Industrial kiln temperature (Tg Sim).*

## 4. CONCLUSIONS

In this study, the firing operations and sintering of ceramic tiles in roller kilns were evaluated in the laboratory and industrially. This was done by modelling and numerical simulation of sintering and the phenomenon of heat transfer by conduction, respectively.

The results of the linear shrinkage in the numerical simulation exhibit significant agreement with the experimental data obtained in the laboratory and industrially, so that this tool can be used to evaluate the behaviour of ceramic tiles with different compositions after different firing curve conditions. This tool could therefore serve to optimise the firing operation of red-body stoneware tile.

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