EXPERIMENTAL DRYING OF CERAMIC BRICKS INCLUDING SHRINKAGE

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Abstract: *The ceramic industry in Brazil still presents industrial processes with a great consumption of energy, mostly associated with a high environmental impact. In this context, the great majority of these industries produces products of low quality due to inadequate processes of drying, presenting then a great technological delay. Therefore, the aim of this study is to contribute for the improvement of the quality of the drying process presenting an experimental study of the drying samples (geometrically parallelepiped) of two clay types, with different dimensions , and different initial humidity contents. In the drying settings, several air temperatures as well as several relative air humidities were used, and thus several curves of the drying kinetics and of shrinkage are shown and analyzed. The drying process takes place in the period of decreasing rate and the shrinkage happens in two periods.*

***Keywords**:* drying, experimental, mass, shrinkage, clays, parallelepipedal solids.

1. Introduction

Drying is a process of heat and mass transfer including shrinkage that takes place in porous bodies. During clay drying, the main parameter to obtain optimum drying is the maximum drying rate so as to prevent cracks, fissures and deformations.

Many researchers have reported on the drying of clay, such as Elias (1995), Fricke (1981), Ketelaars et al.(1992), and Hasatani & Itaya (1992), van der Zanden et al. (1996); van der Zanden et al. (1997) Medeiros (1997), and Reed (1991).

During the drying of solids, the shrinkage phenomenon exists, and it alters their drying kinetics and their dimensions. This phenomenon happens simultaneously with the moisture transport and it is more intense in ceramic materials with high initial moisture content, and mainly in products of fine granulation. Depending on the drying conditions, the structure of the material and of the geometry of the product, the shrinkage phenomenon can cause cracks, deformations and even fractures inside the solids. Therefore, it is very important to study drying with the inclusion of shrinkage.

In the mathematical modeling with the inclusion of the shrinkage, the relative properties of the phenomenon will be incorporated to the model. However, in the literatures on drying, there is scarce information on the shrinkage coefficients, as well as of mathematical relationships among mass diffusivity, shrinkage and density. Besides, as we found in the literature, curves of linear shrinkage versus moisture content --for example in Elias, (1995), Reeds (1991), and Norton, (1975).

In this sense, there are other studies that include the volumetric shrinkage in ceramic materials such as Itaya and Hasatani (1997); Keteraals et al. (1992); Hasatani and Itaya, (1992); Itaya and Hasatani,(1996), Nascimento et al. (2001a-b), and Nascimento et al. (2005). Thus, studies in an area such as the one of ceramics--that has a gigantic potential of growth-- will favor the improvement of the drying process.

2. Experimental procedure

For this experimental study two different types of clay are used to analyze the effect of air temperature and body shape on the drying rate. The chemical composition of the each material is shown in table 1.

Table 1 – Chemical composition of the clays

Red ceramic	Chemical composition (%)							
	Fe_2O_3	Al_2O_3	SiO_2	CaO	MgO	Na_2O	K_2O	Pr
	7,58	23,97	52,70	0,56	4,04	0,62	1,25	——
Ball-clay	1,35	32,12	51,02	——	0,73	——	——	8,95

The ceramic bricks (red and ball clay types) were made press-molded on the parallelepipedal shape under pressing pressure of 2.5 MPa. The bricks were dried by placing them in an oven in different temperatures and relative air humidities. The first step of each experiment was to weigh the samples and to measure their length in intervals of 10 minutes during the drying process. The mass of the samples was obtained by an electronic scale with accuracy of ±0.01g and the dimensions of the samples were measured using a digital pachimeter with accuracy of ± 0.01mm. The velocity was measured using an anemometer and the relative air humidity by a hydrometer.

The continuous drying experiments ended when the mass reached constant weight. In order to obtain the equilibrium moisture content and their drying mass, all the samples remained in the same temperature for 48 hours. All tests were performed at an atmospheric pressure. Table 2 presents all ceramic bricks drying conditions used in this study. In this table, for example, code E110R1 represents Experiment to the 110 ^{o}C with Red ceramic number 1 and code E110BA1 represents Experiment to the 110 ^{o}C with Ball-Clay ceramic while t represents total drying time.

Table 2 -Experimental conditions used in this work

Samples	Air			Ceramic bricks					t (min)
	T (^{o}C)	RH (%)	v (m/s)	M_o (d.b.)	M_e (d.b.)	L (mm)	C (mm)	H (mm)	
E110BA1	110	2.18	≈0.0	0.0808	0.00069	20.35	60.67	6.50	220
E110BA2	110	2.18	≈0.0	0.0777	0.00181	20.48	60.66	5.11	220
E110BA3	110	2.18	≈0.0	0.1460	0.00129	20.31	60.43	7.06	220
E80BA1	80	4.66	0.1	0.0773	0.00097	20.56	60.81	4.76	220
E80BA2	80	4.66	0.1	0.0769	0.00181	20.56	60.80	5.09	220
E80BA3	80	4.66	0.1	0.0765	0.00084	20.49	60.81	5.39	220
E60R1	60	10.00	0.1	0.0960	0.01047	60.24	120.77	7.52	360
E60R2	60	10.00	0.1	0.0950	0.01017	60.37	120.80	7.00	360
E80R1	80	4.96	0.1	0.2139	0.00158	20.55	60.26	6.55	270
E80R2	80	6.00	0.1	0.0930	0.00115	60.12	120.24	7.17	330
E110R1	110	2.00	≈0.0	0.1030	0.000499	64.35	120.75	7.45	300
T – Air temperature (ºC) – RH – Relative Air humidity (%) – v - Air velocity (m/s)									

According to Lima (1999), the following equation was utilized to obtain the volumetrical changes in each time during the drying process:

$$(V)_t = V_o\left(\bar{\beta}_1 + \bar{\beta}_2 \overline{M}\right) \quad (1)$$

Since in t = 0, $\overline{M} = \overline{M}_o$, and $(V)_t = V_o$, we have that $\bar{\beta}_1 = \left(1 - \bar{\beta}_2 \overline{M}_o\right)$. Then the equation (1) can be written as follows:

$$\frac{(V)_t}{V_o} = 1 - \bar{\beta}_2\left(\overline{M}_o - \overline{M}\right) \quad (2)$$

The equation (2) can be re-written as follows:

$$\frac{(V)_t}{V_o} = \bar{\beta}_3 + \bar{\beta}_4 \overline{M}^* \quad (3)$$

Where $\bar{\beta}_3 = \bar{\beta}_1 + \bar{\beta}_2 \overline{M}_e$, $\bar{\beta}_4 = \bar{\beta}_2(\overline{M}_o - \overline{M}_e)$ $\overline{M}^* = (\overline{M} - \overline{M}e)/(\overline{M}o - \overline{M}e)$, and $\bar{\beta}_1, \bar{\beta}_2, \bar{\beta}_3, \bar{\beta}_4$ are the volumetrical shrinkage coefficients that were obtained by fitting using the Rosembrock and quasi-Newton method with convergence criterion of 0.001. (3). $\overline{M}_o$, $\overline{M}_e$ and $\overline{M}$ are respectively the average initial moisture content, the average equilibrium moisture content in a dry-basis and average moisture content kg/kg. The shrinkage occurred in two drying periods

In many industrial processes the drying rate equations have been proposed by several authors. In this sense, a number of researchers have used series solution to estimate the drying rate as follows:

$$\overline{M}^* = \sum_{i=1}^{N} A_i exp^{(-K_i t)} \quad (4)$$

The terms of this convergent series diminish by increasing N and t.Various approximations and variations of the diffusive model have been used to predict the drying rate of many solids. However, relatively little studies are related to ceramic materials. In this sense, it was proposed an approximate form of the Eq. (4) when only three terms of the infinite series is used. In this manner, we can write:

$$\overline{M}^* = A_1 exp^{(-K_1 t)} + A_2 exp^{(-K_2 t)} + A_3 exp^{(-K_3 t)} \quad (5)$$

Where A_i and K_i are constants that were determined by fitting to the experimental data for each drying condition, using the Rosembrock and quasi-Newton method with convergence criterions of 0.001.

3. Results and discussions

The estimate value of the volumetric shrinkage coefficient in the Eq. (3) applied to ceramic bricks in six experiments are presented in the Tab 3. The correlation coefficient in all experiments was higher than 0,91. The comparison curve between the experimental shrinkage data and the data that fits the equation is shown in Fig. 1-2.

Table 3. Volumetric shrinkage and correlation coefficients (R) and variance ($\bar{S}^2$) for all drying experiments

	1st step of shrinkage				2nd step of shrinkage			
Samples	$\bar{\beta}_3$	$\bar{\beta}_4$	R	$\bar{S}^2$	$\bar{\beta}_3$	$\bar{\beta}_4$	R	$\bar{S}^2$
E110R1	0.9736845	0.0268727	0.964	0.626	0.9682333	0.0881264	0.968	0.938
E110BA3	0.9923750	0.0081330	0.970	0.934	0.9841877	0.3072390	1.000	1.000
E80R1	0.7886403	0.1854330	0.924	0.853	0.7991150	0.2814140	0.972	0.945
E60R2	0.982623	0.0173892	0.981	0.962	0.971364	0.1385793	0.975	0.950

In the beginning of the drying process, there is a big moisture removal so the dimensions of the solid changes with high velocity. Thus, the shrinkage velocity approaches zero. The point where the shrinkage presents a new behavior is different depending on the composition of the material.

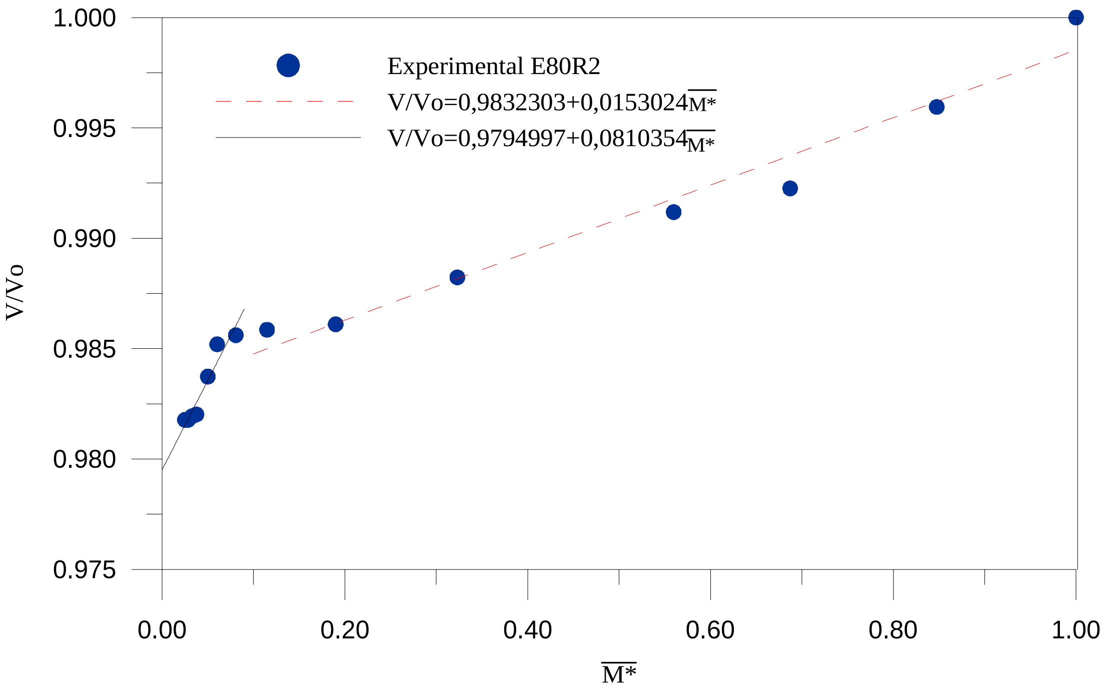

Figure 1 - Comparison between the experimental (o) and the predicted volumes of red ceramic bricks obtained during the drying in an oven to the T=80 °C.

In these figures we can see the existence of two periods with volumetrical changes. This behavior is in concordance with the results of Hasatani and Itaya (1992a-b) and Ketelaars et al. (1992). According to Elias (1995), the point where the curves intercept is called critical moisture content. However, in this study no constant drying period was encountered because the initial moisture content was low.

In order to analyze the effects of the air drying conditions on the moisture content removal of the ceramic bricks, the experimental data of moisture content for many experiments are plotted in the Figs. 3 - 4.

By comparison, among the data, we can see that the air-drying temperature presents a high influence on the drying rate, as expected. When the temperature increases, the drying rate increases too. This is not very desirable because it can generate high temperature gradients in the inside of the solids and therefore induce thermal and mechanical stress. This stress may produce cracks, fissures and deformations, and contribute to reduce the quality of the solids in the end of the process of drying. According to Hasatani and Itaya (1992a-b) and Hasatani and Itaya (1996), the mechanical behavior of clay is generally described by viscoelasticity and plasticity depending of the moisture content.

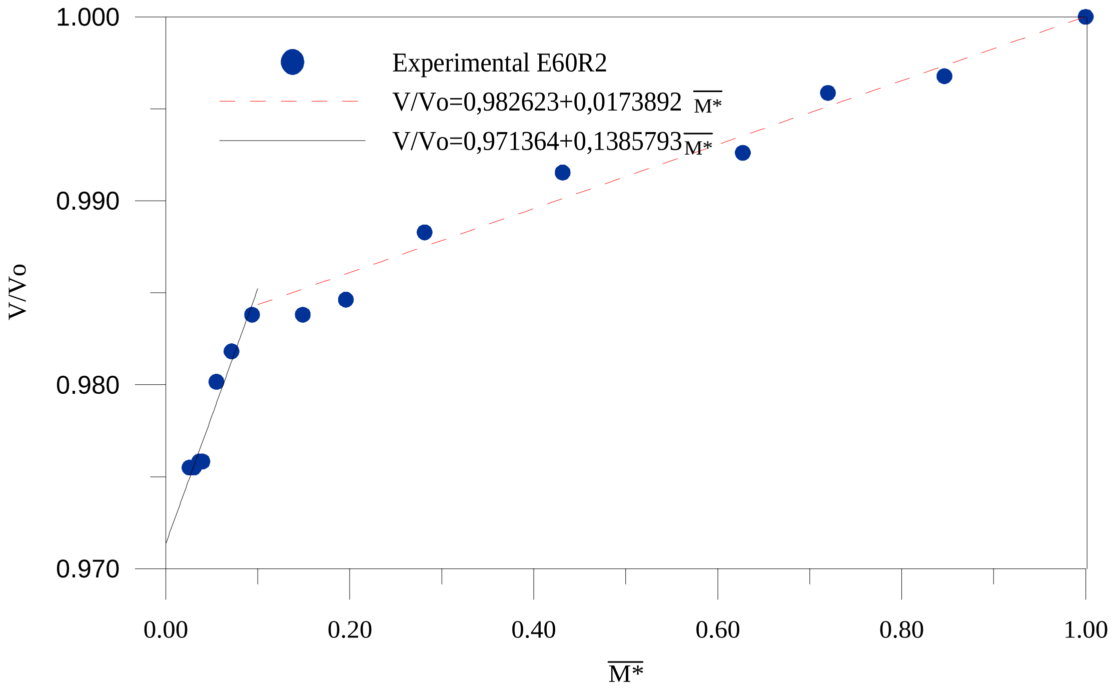

Figure 2 - Comparison between the experimental (o) and the predicted volumes of red ceramic bricks obtained during the drying in the oven to the T=60 °C.

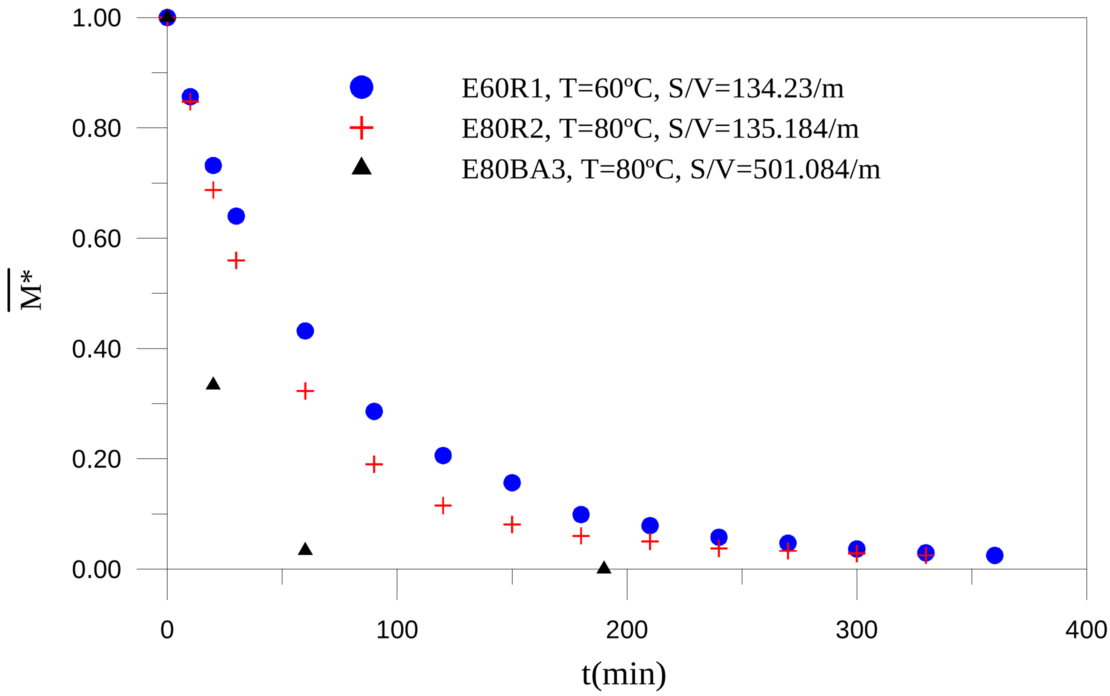

Figure 3. Influence of the shape of the solids and of the air temperature on the dimensionless mean moisture content during the ceramic bricks drying process.

The shapes of the bricks affect the drying rate too. For higher relationships area/volume we have the highest drying velocity, as expected. According to Nascimento et al. (2001) and Hasatani and Itaya (1996) the highest moisture and temperature gradients occur near the vertices of the solid. Therefore, this region is more favorable to cracks and fissures.

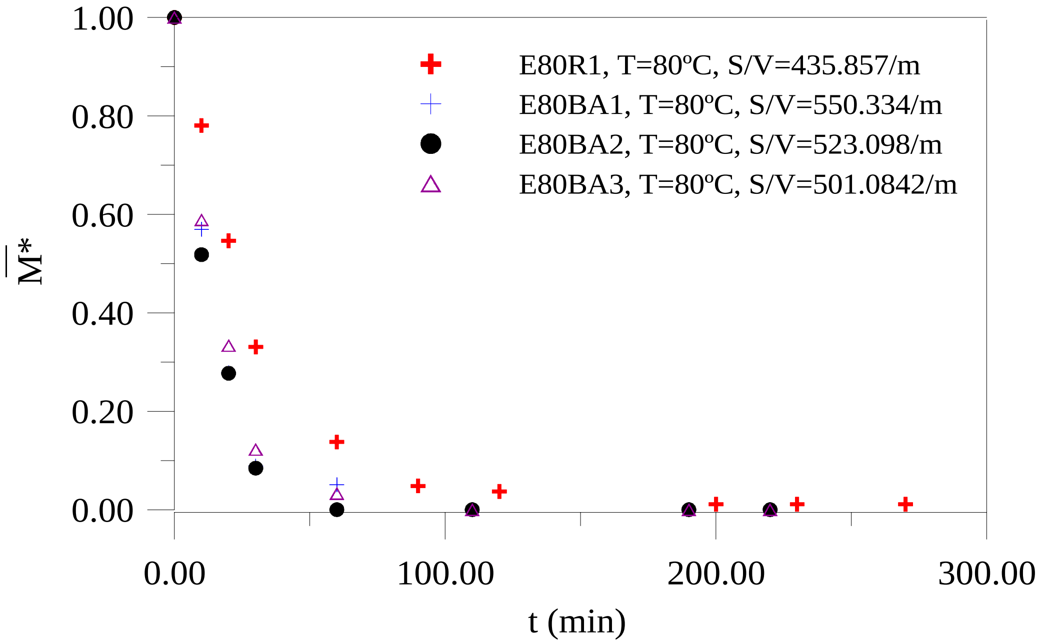

Figure 4 - Influence of the shape of the solid on the dimensionless mean moisture content during the ceramic bricks drying process T= 80 ^{o}C.

Non-linear regression technique was used to obtain values of A and K. The table 4 presents these values. As we can see, excellent fittings were obtained for each test data where the values of the regression coefficient were R > 0,98.

Table 4. Parameters of the equation (5) determined by fitting the experimental data for each drying condition.

Test	Exp. point	Parameters						R
		A_1	$K_1(s^{-1})$	A_2	$K_2(s^{-1})$	A_3	$K_3(s^{-1})$	
E110BA3	5	0,3433845	0,0012352	0,3445390	0,0012353	0,3445407	0,0012253	0,983
E80R1	9	0,3312750	0,0005531	0,3453080	0,0005532	0,3471225	0,0005531	0,997
E110R1	5	0,2719987	0,0027532	0,3454675	0,0009327	0,3944376	0,0006337	0,990
E60R1	10	0,9172583	0,0003280	0,0807159	0,0030180	0,0022671	0,0002000	0,998
E60R3	9	0,2004540	0,0062995	0,0365420	0,0000203	0,7653440	0,0002921	0,999

These results can be used to help other researchers in future studies on the drying of ceramics bricks

4. Conclusions

Drying experiments have been carried out to obtain a better understanding between drying rate of ceramic bricks and the various drying parameters.

The experimental data has been fit to a three-term exponential using a thin-layer drying model with six parameters. As a result of this study, the following main conclusions can be summarized:

⇒ Fundamental equation assumption shrinkage was developed and presented.

⇒ The influence of temperature as the main factor in the drying rate was confirmed. As temperature increases, the drying rate is higher and total drying time is shorter. The same behavior was verified to relationships area/volume.

⇒ It was verified that shrinkage is present in the moisture removal of ceramic bricks during the drying process and it is one important factor in the quality of the product at the end of the process.

⇒ The existence of two periods of volumetrical changes was verified.

⇒ The results of the study gave us a basis to calculate the transport coefficient of ceramic bricks during the drying process in future studies.

⇒ The thin-layer drying model has fit to the experimental data ,and presented a reasonable agreement, where the regression coefficient was higher than 0,91.

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