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Microwave Drying Kinetics of a Clay-Plate

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Abstract: This study presents the development of an exponential model for the description of kinetics in the drying process of a porous material under the condition of dielectric heating. The model describes the changes in moisture content and in the rate of drying related to the duration of the process, as well as the moisture content in the material to be dried with the power of microwave drying as parameter. The item defined is the functional dependence of the model coefficients on the power of the microwave drying. An expression to compute the drying time as a function of the moisture content in the sample and the power of the microwave drying is suggested. The results of the experiment and those obtained from the application of the model based on the computed ratio between the moisture content and dry matter correspond to an extraordinarily high degree.

1 INTRODUCTION

Advances in the drying technology of porous material have been increasingly stimulated over the past years, so that, in contrast to the traditional convective drying with warm air, other drying methods are becoming more and more important. In this context, the possibility of application of high-frequency drying in the drying process of a porous material is put into the centre of interest.[1–10] Some of the studies[11,12] deal with the possibility of predicting the rate of heating up the material exposed to microwaves. Other studies[13,14] are concerned with the specific acceleration of drying by the means of microwaves.

Mathematical models are necessary in analyzing, designing, simulating and conducting the drying process. The complexity of an appropriate model depends on its purpose. Dynamic simulation as well as conduct of this process require more comprehensive models, while simple models meet the requirements of designing or presenting the technical calculation. The comprehensive models mentioned above are generally very complex and more time consuming than the latter, and their actual application often does not justify the time spent on their development. From the point of view of every designer, the first thing to bear in mind is a comprehensive understanding of drying kinetics. It provides the basic information for a designer to help him choose the technique and drying devices so as to obtain a good quality product with the least possible energy consumption. The more simple models for drying kinetics mostly contain determination of drying kinetics describing the mechanisms and impact of particular process variables on the moisture transfer. Drying kinetics models commonly used in industry often consist of empirical, semi-theoretical equations which include parameters of phenomenological nature. Although those parameters are not necessarily of physical importance when brought into connection with the appropriate driving force, they can help to anticipate the kinetics of drying. If this is the case, these models can replace the more complex ones. On the basis of this approach, some models have already been presented.[15–30] The results of these models which correspond to the experimental output still leave enough room for further improvement in the field of drying kinetics.

The experiments described in this study were performed in order to find an appropriate model for the kinetics of microwave drying with parame-

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ters represented as the function of the power of microwave drying in the drying process.

2 RESULTS

The microwave drying experiments were performed on clay-plate samples, dimensions 138 × 65 × 16 mm, cut from industrially manufactured plane roofing tiles. The samples cut in this way were prepared to resemble the industrial tiles, both regarding the geometrical shape and the treatment. Preliminary laboratory research on the raw material used in manufacturing of roofing tiles showed that we were dealing with illite–montmorillonite clay containing other minerals such as quartz, kaolinite, feldspars and iron hydroxides. Clay contains 3·8% of rest on the 10 000 holes/cm^2 (DIN 1171), and about 30% of the particles are less than 2 μm. The point at which clinkering appears is 1048°C, the sintering point is at 1100°C, and the baking temperature is 930–950°C. The shrinkage caused by drying is 7–8%, which points to the significant sensitivity of that clay while drying.

The drying experiments were performed in the laboratory test apparatus for microwave drying (Fig. 1). The apparatus consists of the microwave oven used in households (vol. 20 l, power supply 1200 W, and microwave heating power 750 W), an electronic balance for measuring the mass of the sample with accuracy of ± 0·01 g, and an electronic thermometer for measuring the temperature of samples during the process of drying with an accuracy of ± 0·1°C. The apparatus has been constructed to enable the continued measuring of mass and temperature of the drying sample.[31]

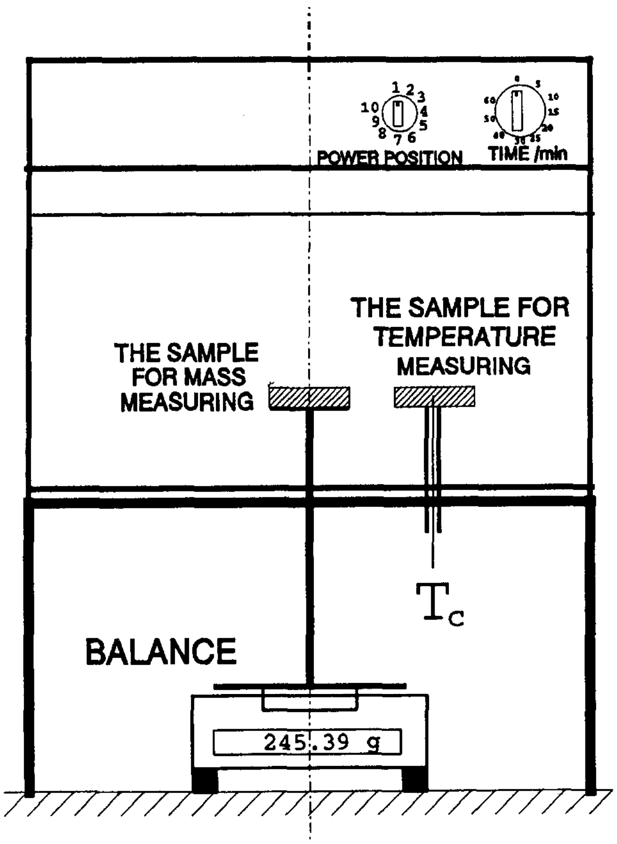

Fig. 1. Scheme of the laboratory test device for microwave drying.

The mass of the sample was measured from one sample of the stated dimensions and the temperature from another, of the same dimensions, placed next to the sample for mass measuring, but in such a way as not to disturb the measuring of the mass.

A number of experiments were carried out at different levels of microwave drying power (P). The experiments were performed under constant conditions relevant to each of them, with the emphasis on the maximum possible power of microwave drying at which it was still possible to obtain a good-quality dried roofing tile. The levels of microwave drying power were as follows:

MW-1: P = 10 Wkg$_{sm}^{-1}$
MW-2: P = 13 Wkg$_{sm}^{-1}$
MW-3: P = 20 Wkg$_{sm}^{-1}$
MW-4: P = 27 Wkg$_{sm}^{-1}$
MW-5: P = 33 Wkg$_{sm}^{-1}$

Drying at $P > 33$ Wkg$_{sm}^{-1}$ caused deformations or cracks in the sample, which means that drying of a moist clay-plate under conditions from the beginning to the end of the drying process is possible at maximum P = 33 Wkg$_{sm}^{-1}$. The labels MW-1, MW-2, ..., MW-5 will further be used as the labels of the experiment carried out at the above quoted levels of microwave drying power, respectively. The experimental results are presented in Figs 2 and 3.

In order to find a mathematical model for the microwave drying kinetics description a numerical method of regression was used. Thus, the analytical exponential expression was tested by means of the regressive numerical method of the least squares,

$$\zeta(t) = \zeta_0 \cdot \mathrm{EXP}(-kt^n), \qquad (1)$$
$$(-\mathrm{d}\zeta(t)/\mathrm{d}t) = nkt^{(n-1)}\zeta(t)$$
where $t \geq 0$, $a > 0$, $k > 0$ and $n > 1$,

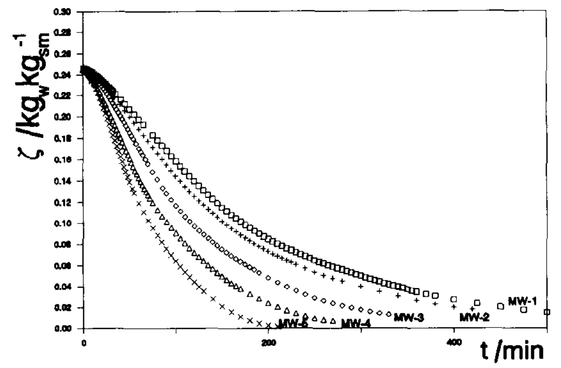

Fig. 2. Dependence of the moisture content of the samples on the microwave drying time.

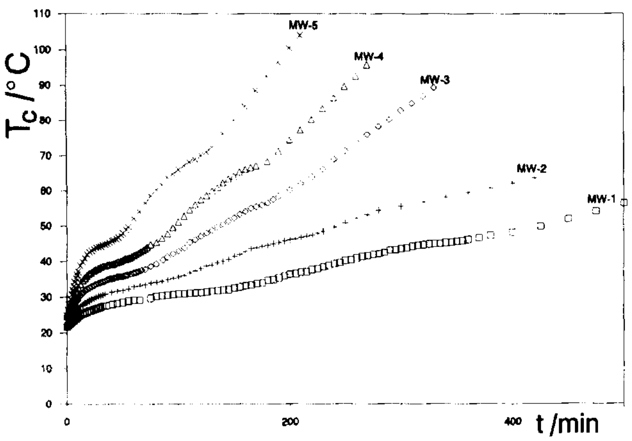

Fig. 3. Dependence of the temperature in the mass centre of the samples on the microwave drying time.

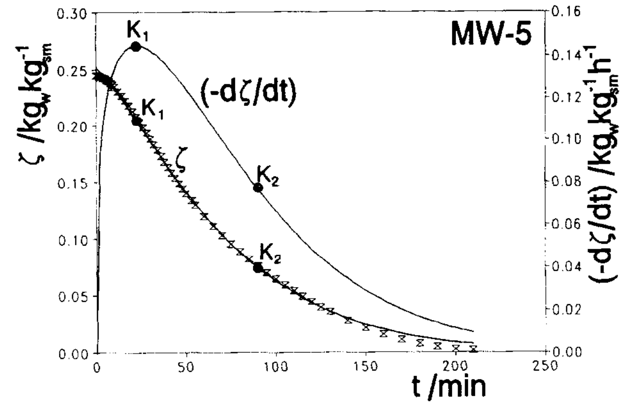

Fig. 4. Approximation of the drying kinetics for the experiment MW-5 by model (1).

as the approximate model for the microwave drying kinetics. The acceptability of this model was tested by computing the correlation index (ρ) and the mean-square deviation (σ). The results are given in Table 1, and, as an example for the MW-5 experiment, in Fig. 4.

The first critical point was defined as the maximum of the drying rate function ((-d$\zeta(t)$/dt)),

$$t_{K,1} = ((n-1)/(kn))^{(1/n)}$$
$$\zeta_{K,1} = a \cdot \mathrm{EXP}((1-n)/n)$$
$$(-\mathrm{d}\zeta/\mathrm{d}t)_{max} = knt_{K,1}^{(n-1)}\zeta_{K,1},$$

and the second critical point as the inflection point of the drying rate function,

$$t_{K,2} = ((2n-1)/(kn))^{(1/n)}$$
$$\zeta_{K,2} = a \cdot \mathrm{EXP}((1-2n)/n).$$

The results revealed that the drying coefficients, k and n, are linearly dependent on the power of microwave drying (P). Their dependence can be obtained from the approximation functions,

$$k = 1{\cdot}604{\cdot}10^{-3} + 7{\cdot}394 \cdot 10^{-5} \cdot P \quad (2)$$

$$n = 1{\cdot}096 + 4{\cdot}992{\cdot}10^{-3} \cdot P \quad (3)$$

By the means of model (1) and obtained values for functional dependence, (2) and (3), and by assigning the parameter a in model (1) the initial moisture content of the sample ($a = \zeta_0$) it is possible to simulate the microwave drying kinetics. Thus, the simulation of microwave drying kinetics at the constant power of microwave drying can be obtained from the model,

$$\zeta = \zeta_0 \cdot e^{(-(1{\cdot}604 \cdot 10^{-3} + 7{\cdot}394 \cdot 10^{-5} \cdot P) \cdot t^{(1{\cdot}096 + 4{\cdot}992 \cdot 10^{-3} \cdot P)})} \quad (4)$$

The results obtained from the simulation are shown in Figs 5 and 6. It is obvious that simulation of microwave drying kinetics has been successful.

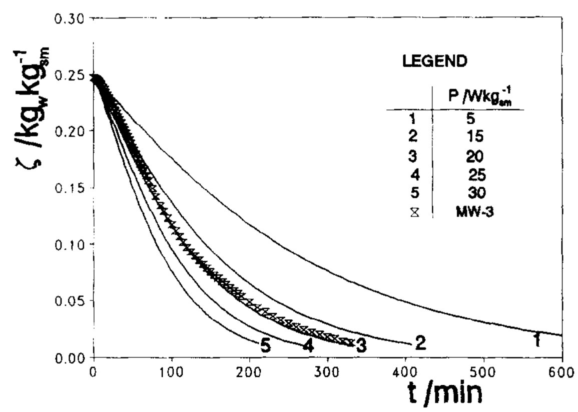

Fig. 5. Simulation of drying kinetics by model (4) at different levels of microwave drying power with the same initial water content of the clay samples.

Table 1. Results of approximation of microwave drying kinetics from model (1)

Parameters	MW-1	MW-2	Experiment MW-3	MW-4	MW-5
a	0·2512	0·2513	0·2530	0·2490	0·2513
$k \cdot 10^3$	2·351	2·569	3·080	3·569	4·069
n	1·150	1·161	1·190	1·225	1·267
ρ	0·99941	0·99945	0·99948	0·99968	0·99939
σ	0·00272	0·00254	0·00257	0·00197	0·00288
$t_{K,1}$(min)	32·86	30·77	27·60	24·96	22·54
$\zeta_{K,1}$($kg_w kg_{sm}^{-1}$)	0·2205	0·2187	0·2157	0·2072	0·2035
$(-\mathrm{d}\zeta/\mathrm{d}t)_{max}$($kg_w kg_{sm}^{-1}h^{-1}$)	0·06040	0·06795	0·08910	0·11210	0·14462
$t_{K,2}$(min)	214·85	188·70	146·05	114·22	89·60
$\zeta_{K,2}$($kg_w kg_{sm}^{-1}$)	0·0811	0·0805	0·0793	0·0762	0·0749
$t_k(\zeta = 0{\cdot}02 kg_w kg_{sm}^{-1})$ (min)	488·74	378·78	282·05	211·76	160·34

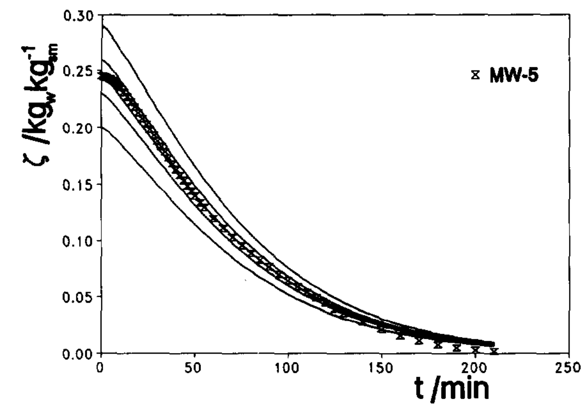

Fig. 6. Simulation of drying kinetics at $P = 33\ \mathrm{Wkg_{sm}^{-1}}$ with different initial water content of the clay sample, (ζ_0), by model (4).

On the basis model (1), an expression for computing the duration of the microwave drying period as a function of water content in the sample and the power of microwave drying can be obtained,

$$t = \left(\frac{1}{k} \ln \frac{a}{\zeta}\right)^{1/n} \qquad (5)$$

3 CONCLUSION

It has been established that the experimental results of microwave drying can be highly approximated with the model,

$$\zeta(t) = \zeta_0 \cdot \exp(-kt^n),$$
$$(-\mathrm{d}\zeta(t)/\mathrm{d}t) = nkt^{(n-1)}\zeta(t)$$
$$k = 1{\cdot}604 \cdot 10^{-3} + 7{\cdot}394 \cdot 10^{-5} \cdot P$$
$$n = 1{\cdot}096 + 4{\cdot}992 \cdot 10^{-3} \cdot P.$$

The proposed model enables simulation of kinetics serving as the basis for conducting the microwave drying process.

From this model, the expression for computing the duration of the microwave drying process was obtained as a function of the microwave drying power, the initial water content (ζ_0), and the level of water content to which the porous material is dried (ζ),

$$t = \left(\frac{1}{k} \ln \frac{\zeta_0}{\zeta}\right)^{1/n}.$$

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