*Chemical Product and Process Modeling*

*Volume* 5, *Issue* 1 2010 *Article* 4

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**Recommended Citation:**
Pillai, Magesh Ganesh; Regupathi, Iyyasamy; Miranda, Lima Rose; and Murugesan, Thanapalan (2010) "Moisture Diffusivity and Energy Consumption during Microwave Drying of Plaster of Paris," *Chemical Product and Process Modeling*: Vol. 5: Iss. 1, Article 4.
**DOI:** 10.2202/1934-2659.1316

# Moisture Diffusivity and Energy Consumption during Microwave Drying of Plaster of Paris

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## Abstract

The drying characteristics of plaster of paris (POP) under microwave conditions at different microwave power input, initial moisture content, sample thickness and drying time were studied. Further the experimental data on moisture ratio of POP for different operating conditions were obtained and calculations were made using nine basic drying model equations. The appropriate model with modified constants and coefficients to represent the drying kinetics of POP was found through the analysis of the statistical analysis. The effective moisture diffusivity of the drying process was also computed for different experimental conditions and a relationship between the drying rate constant and the effective moisture diffusivity was obtained. The energy consumption for microwave drying of plaster of paris at different experimental conditions were also computed.

**KEYWORDS:** plaster of paris (POP), microwave drying, drying rate constant, energy consumption, effective moisture diffusivity, micro structure

**Author Notes:** The authors acknowledge the Defense Research and Development Organization (DRDO), Government of India for providing research fellowship to Mr. Mahesh Ganesapillai and providing financial support to facilitate the experimental research work.

## 1. Introduction

In ceramic production, drying of molded materials generally requires longer time than other stages, during which the drying rate gets reduced. The reduction in drying rate enhances the deformation of sample, generation of defectives, trims down the quality of dry products, etc, while increase in drying rate, reduces the drying time, and increases internal moisture transfer as well as heat transfer (Gong et al., 1998; Itaya et al., 1997). Drying of thin slabs by multimode heat input with convection, conduction or radiation causes shrinkage, color change in material (due to prolonged exposure), as in the case of conventional drying with hot air (solar drying, open air drying, single layer solar drying, convective type tray dryer, etc). Their disadvantages include inability to handle the large quantities and to achieve consistent quality standards, contamination problems, long drying times, low energy efficiency and high costs, which are not desirable for commercial applications (Maskan, 2000; Soysal and Oztekin, 2000). Microwave heating provides a potential counter measure to offset these limitations. Microwave is a promising candidate for internal heating. The use of microwaves as a source of energy is rapidly growing and getting convenient advantage over other conventional process for drying. In addition, internal heating of a molded body with a proper control would increase the internal vapor pressure, and may lead to faster moisture migration. In microwave drying, heat is supplied from microwave irradiation to thermal energy within the moist sample, which may result in a rapid dehydration as a result of favorable vapor pressure and temperature gradients. During microwave drying processes, the heating period is relatively short (Bouraoui, 1994).

Plaster of Paris, a basic salt of calcium sulfate with half molecule of water of crystallization ($CaSO_4 \frac{1}{2} H_2O$) is made by calcining the mineral gypsum. When the powdered hemihydrate is mixed with water to form a paste or slurry (also called a slip), the calcining reaction is reversed and a solid mass of interlocking gypsum crystals with moderate strength is formed. Upon setting there is very little (a slight contraction) dimensional change, making the material suitable for accurate molds. The hardened mass is not a compact solid, but a highly porous material with a relatively large internal surface consisting of interlocking crystals in the form of plates and needles. Plaster, known for its porosity and strength, is used as fire resistance on residential and other structures, bone repair cement, ceramic industry for the preparation of models, moulds, gypsum plaster boards and decorative picture frames, interior decoration of buildings and other establishments, etc. The conditions of moisture removal in molded plaster of paris can be changed to adjust the porosity of the hemihydrate, resulting in the formation of alpha and beta hemihydrates, which are chemically identical. The morphology of plaster of paris crystals depend on the formation conditions and the drying methodology put into practice.

Mathematical modeling of the dehydration process is very useful in the design and optimization of dryers (Bertin and Blazquez, 1986; Brook and Bakker, 1978; Vagenas and Marinos, 1991). However, theoretical simulations of the drying process (moisture migrations in the product being dried) require a substantial amount of computing time because of the complexity of the diffusion equations governing the process (Sharp, 1982; Parry, 1985). A number of complex theoretical models to describe the heat and mass transfer phenomena during drying are available in the literature. Availability of such correlations and models, verified by experimental data, will enable engineers and operators to provide optimum solutions to different aspects of drying operations such as energy use, operating conditions and process control, without undertaking experimental trials on the system (Dincer, 1998). In particular, thin-layer equations contribute to the understanding of the heat and mass transfer phenomena, and computer simulations, for designing new processes and improving existing commercial processes (Kardum et al., 2001). Several experimental studies and modeling methodologies have been reported by various investigators for different products on drying characteristics and kinetics (Sacilik and Elicin, 2006; Sharma and Prasad, 2005; Yaldız and Ertekin, 2001a). Farrel et al., 2005).

The objective of the present study is to investigate the effect of different levels of microwave power output, initial moisture content and sample thickness on drying kinetics of plaster of paris and to suggest a suitable model (among the available models) to represent the data and also establish the constants and coefficients for further calculations of effective moisture diffusivity and energy consumption for microwave drying of plaster of paris at different experimental conditions.

## 2. Methods and Materials

### 2.1 Materials:

Rectangular shaped cuboids were molded by mixing commercially available high purity, analar grade plaster of paris (SRL India Ltd. Mumbai) with small quantities of de-ionized water in the ratio 3:2. Slip casting was undertaken at normal ambient temperature, the freshly molded samples were initially tempered, which allows time for the internal moisture and temperature gradient during the resting period. Tempering was done for a period of 18 to 24 hours, so that the material becomes rigid and stable. A series of drying experiments were performed in which the amount of water (70 - 80%) contained in the mould was determined.

## 2.2 Drying Equipment and Drying Procedure:

The microwave drying of plaster of paris was carried out with a 900W, 2.45GHz microwave oven (SAMSUNG C-103F model) having inner chamber dimension of 352 (W) x 220(D) x 300(H) mm equipped with a special device allowing continuous supply of microwave power at controllable level from 100 to 900W with increments. As the commercially available microwave oven has its own limitation in that of monitoring the sample weight, an inbuilt weighing system was introduced to measure the sample weight at any instant (Tee Slaw Koh, 1980). Initially the turntable was dismantled and removed from the cavity. A circular opening of 25mm was made at the bottom of the microwave chamber in the center, through which, a teflon made weighing beam was introduced to hold the sample at its top. The bottom of the beam was placed in the top loading electronic balance cell (sensitivity ±0.01 grams) beneath the drying chamber for intermittent recording of sample weight, which enabled the online weighing of the samples. The electronic load cell remained unaffected by the microwave, since they are calibrated before experimentation.

Drying of plaster of paris started with initial moisture content and continued until no further changes in their mass were observed which was then taken as the equilibrium moisture content for the later computations. The initial and final moisture contents of the plaster of paris samples were determined by oven method as per AOAC (1960) standards. The experiments were conducted at three different initial moisture contents (70%, 75% and 80%), power range (180W, 360W and 540W) and sample thicknesses (14, 13, 12 and 11mm). All tests were conducted in triplicate and the average values were taken for further calculations. In the drying experiments, care was taken on using plaster of paris with the same dimensions for replications. The mass of the fresh molded plaster of paris chosen for the runs were between 130 to 150 g and were in rectangular cuboids shape whose main length: width: height ratio was 80: 70: 13 (mm). The microwave-dried samples were then placed in a hot air oven set at 105ºC for 24 hrs, until bone dry; finally the weight of the sample was noted.

## 3. Results and Discussion

### 3.1 Drying Kinetic of plaster of paris:

In this study, the experimental drying data of plaster of paris at different initial moisture contents, drying time and output power levels of microwave oven were analyzed to identify the most convenient model among the 9 different expressions (Table 1), defining drying rates as proposed by several authors (Ayensu, 1997; Lui and Bakker, 1997; Agarwal and Singh, 1977; Zhang and Litchfield, 1991; Pal and Chakraverthy, 1997; Westerman et al., 1973; Hederson, 1974; Yagcioglu et al., 1999; Ozdemir and Devres, 1999; Wang and Singh, 1978; Kaseem, 1998; Yaldız and Ertekin, 2001b; Verma et al., 1985; Sharaf-Eldeen et al., 1980; Midilli et al., 2002). Comparing the drying phenomenon with Newton's law of cooling, the drying rate will be approximately proportional to the difference in moisture content between the material being dried and the equilibrium moisture content at the drying conditions, which can be expressed in terms of moisture ratio (MR),:

$$MR = \left[ \frac{(X - X_c)}{(X_o - X_c)} \right] \tag{1}$$

For the present studies, the value of $X_c$ was relatively small/ negligible compared with X or $X_o$ for long drying time. For the present analysis it was assumed that the equilibrium moisture content, $X_c$, was equal to zero, thus the expression for moisture ratio (Akgun and Doymaz, 2005; Thakor et al., 2005) can be simplified to

$$MR = \left[ \frac{X}{X_o} \right] = \left[ \frac{(X - X_c)}{(X_o - X_c)} \right] \tag{2}$$

The goodness of fit was evaluated and used as the primary criterion to select the best equation to account for variation in the drying curves (Yaldız et al., 2001) using the statistical parameters of root mean square error (RMSE), residual sum of squares (RSS) and modeling efficiency (EF). The RMSE gives the deviation between the predicted and experimental values and it is required to approach zero. The EF also gives the ability of the model and its highest value is 1. The goodness of fit of the tested mathematical models to the experimental data was evaluated using the following expressions:

**Table 1. The thin layer drying models proposed by various authors used for present analysis.**

| Sl. No | Model Name | Equation | References |
|---|---|---|---|
| 1 | Newton | $MR = \exp(-kt)$ | Ayensu (1997),<br>Lui and Bakker-Arkema (1997), |
| 2 | Page | $MR = \exp(-kt^n)$ | Agarwal and singh(1977),<br>Zhang and Litchfield (1991). |
| 3 | Henderson | $MR = a \exp(-kt)$ | Pal and Chakraverthy (1997),<br>Westerman et al. (1973). |
| 4 | Logarithmic | $MR = a \exp(-kt) + c$ | Hederson (1974),<br>Yagcioglu et al. (1999). |
| 5 | Wang and Singh | $MR = 1+at+bt^2$ | Ozdemir and Devres (1999),<br>Wang and Singh (1978). |
| 6 | Diffusion | $MR = a \exp(-kt)+ (1-a)\exp(-kbt)$ | Kaseem (1998),<br>Yaldis and Ertekin (2001). |
| 7 | Verma | $MR = a \exp(-kt)+(1-a)\exp(-gt)$ | Verma et al. (1985). |
| 8 | Two Term Exponential | $MR = a \exp(-kt)+(1-a)\exp(-kat)$ | Sharaf-Elden et al. (1980). |
| 9 | Midilli | $MR = a \exp(-k(t^n))+ b t)$ | Midilli et al. (2002). |

$$RMSE = \left[ (1/2) \sum_{i=1}^{N} (MR_{\exp,i} - MR_{pred,i})^2 \right]^{0.5} \tag{3}$$

$$RSS = \sum_{i=1}^{N} (MR_{\exp,i} - MR_{pred,i})^2 \tag{4}$$

$$EF = \frac{\sum_{i=1}^{N} \left(MR_{\exp,i} - MR_{\exp,avg}\right)^2 - \sum_{i=1}^{N} \left(MR_{pre,i} - MR_{\exp,i}\right)^2}{\sum_{i=1}^{N} \left(MR_{\exp,i} - MR_{\exp,avg}\right)^2} \tag{5}$$

where $MR_{exp,i}$ stands for the ‘$i^{th}$’ experimental moisture ratio found in any measurement and $MR_{pred,i}$ is the predicted moisture ratio, and $MR_{exp,avg}$ is the average value of experimental moisture ratio (Midilli and Kucuk, 2003; Togrul and Pehlivan, 2002; Togrul and Pehlivan, 2003). These statistical parameters have been widely used as a primary criterion for the selection of the best equation to account for variation in the drying curves (Togrul and Pehlivan, 2003; Ertekin and Yaldız, 2004; Sarsavadia et al., 1999).

The microwave power supplied to the system plays a major role in shaping the final moisture content, which explains the drying nature of the samples. The effect of microwave output power (180, 360 and 540 W) on moisture ratio and drying rate are shown in Fig. 1. As the microwave output power was increased, the drying time of samples was significantly decreased. During the microwave drying process, the moisture content of plaster of paris was reduced from 80.80 to 13.23 % within 320 seconds at a fixed microwave output power of 180W. As the additional microwave powers (360, 540W) were introduced, the drying time was significantly reduced, whereas the samples cracked at higher orders (540W) of microwave power output. The presence of maximum moisture content in samples responded quantitatively faster to microwave resulting in immediate and complete drying of plaster of paris whereas, samples with less moisture initial moisture content responded slowly.

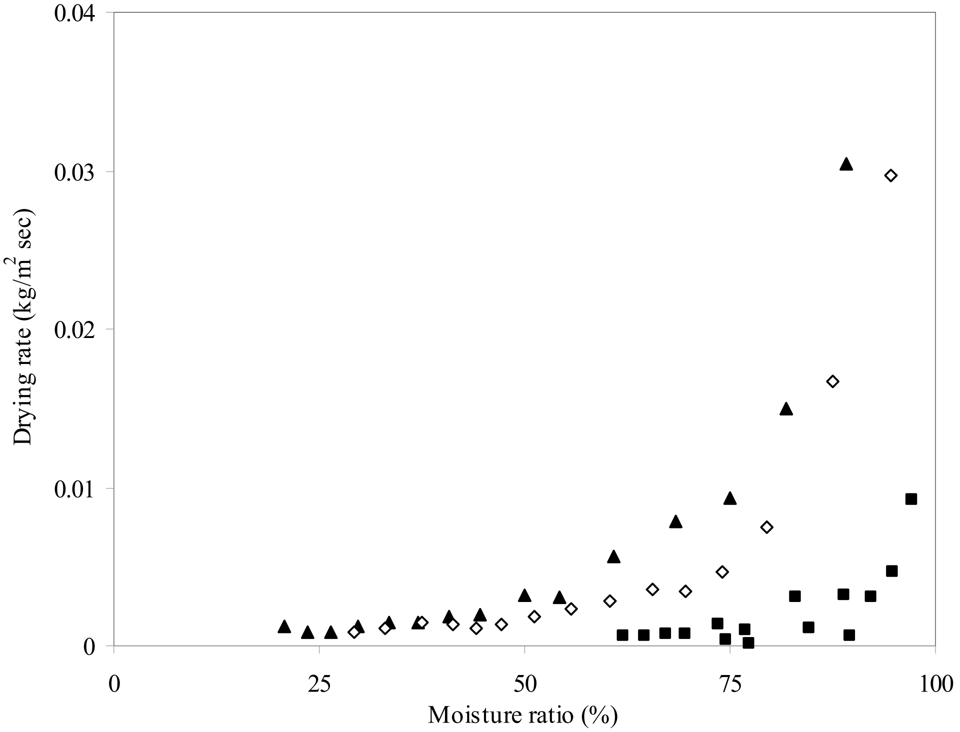


**Fig. 1. Drying rate of sample thickness of 13 mm. and initial moisture content 80 % for various microwave output powers (▲, 180W; ◊, 360W; ■, 540 W).**

Based on the present experiments it was observed that during microwave drying of plaster of paris, there no constant rate period was observed and drying takes place only during the falling rate period in which internal liquid diffusion controls the entire drying process. In view of the fact that the microwave drying process is entirely controlled by internal mass transfer resistance. The obtained microwave drying curves were analyzed using 9 different empirical and semi-empirical drying models (Table 1) through Regression analyses.

**Table 2.** **Statistical analysis of the models at various microwave output powers (Condition : Initial moisture content 80%, Sample thickness : 15mm )**

| Sl. No | Model Name | Microwave output power(W) | Modeling efficiency | RMSE | RSS |
|---|---|---|---|---|---|
| 1 | Newton | 180 | 0.99709 | 0.01128 | 0.00012 |
| | | 360 | 0.99657 | 0.01843 | 0.00034 |
| | | 540 | 0.99614 | 0.03875 | 0.00150 |
| 2 | Page | 180 | 0.99707 | 0.01162 | 0.00013 |
| | | 360 | 0.99657 | 0.01843 | 0.00034 |
| | | 540 | 0.99614 | 0.03875 | 0.00150 |
| 3 | Henderson | 180 | 0.99730 | 0.01109 | 0.00012 |
| | | 360 | 0.99721 | 0.01675 | 0.00028 |
| | | 540 | 0.99234 | 0.06828 | 0.00466 |
| 4 | Logarithmic | 180 | 0.99932 | 0.00702 | 4.94x10$^{-05}$ |
| | | 360 | 0.99909 | 0.01106 | 0.00012 |
| | | 540 | 0.99859 | 0.02402 | 0.00057 |
| 5 | Wang and Singh | 180 | 0.99762 | 0.01328 | 0.00017 |
| | | 360 | 0.99534 | 0.01324 | 0.00017 |
| | | 540 | 0.99517 | 0.01722 | 0.00029 |
| 6 | Diffusion | 180 | 0.99709 | 0.01128 | 0.00012 |
| | | 360 | 0.99657 | 0.01843 | 0.00033 |
| | | 540 | 0.99614 | 0.03875 | 0.00150 |
| 7 | Verma | 180 | 0.99743 | 0.01097 | 0.00012 |
| | | 360 | 0.99749 | 0.01581 | 0.00025 |
| | | 540 | 0.99759 | 0.03107 | 0.00096 |
| 8 | Two Term Exponential | 180 | 0.99709 | 0.01128 | 0.00012 |
| | | 360 | 0.99657 | 0.01843 | 0.00034 |
| | | 540 | 0.99614 | 0.03875 | 0.00150 |
| 9 | Midilli | 180 | 0.99955 | 0.00640 | 4.11E-05 |
| | | 360 | 0.99924 | 0.01021 | 0.00010 |
| | | 540 | 0.99905 | 0.01970 | 0.00038 |

Among all those, Midilli's model was found to be the most appropriate one to represent the present experimental data with the values for the efficiency was greater than 0.99905 and the standard error and RSS less than 0.00640 and 4.11x $10^{-5}$, respectively, as given in Table 2.The results obtained in this study are in accordance with the previous investigators results, obtained with a linear and a power equation for apricots (Togrul and Pehlivan, 2002). The estimated parameters of this model, k, n, a, and b for a given drying condition are presented in Table 3. It was further observed that the value of the drying rate constant (k) increased with decreasing microwave power output.

**Table 3. The estimated parameters of model equations at various microwave output powers (Condition : Initial moisture content 80%, Sample thickness : 15mm )**

| Model name | Microwave Power (W) | Constants | | | |
|---|---|---|---|---|---|
| | | k | n | a | b |
| Midilli | 180 | 0.00569 | 0.94836 | 0.99819 | -0.00026 |
| | 360 | 0.00467 | 0.88876 | 1.00731 | -0.00062 |
| | 540 | -0.00073 | 0.62800 | 0.98739 | -0.00242 |

From Fig. 2. it can be seen that as the thickness of the sample increased, the time required to achieve certain moisture content level was increased and dehydration occurred slowly. It was further noticed that the dehydration rate was higher in the thinner samples at the same level of moisture content. During the microwave drying, the internal heat is generated inside the plaster of paris mold, internal moisture move easily to surface and the dehydration rate will increase. However, increase in the thickness will increase the energy required for the moisture transfer due to the volumetric heating of the sample, generating high vapor pressure of moisture, inside the samples. The microwave drying process, which reduced the moisture content of plaster of paris from 79.67 % to 4.68% (wet basis), as the sample thickness was 11 mm, while working at 14 mm the reduction was only from 80.22 to 19.2%. Amongst the nine semi- empirical thin layer models used to describe the effect of diverse thicknesses of plaster of paris on its drying kinetics, Midilli's model was again found to be the most suitable one for all the experimental data as shown in Table 4. The estimated constants of Midilli's model, k, n, a, and b are presented in Table 5.

DOI: 10.2202/1934-2659.1316

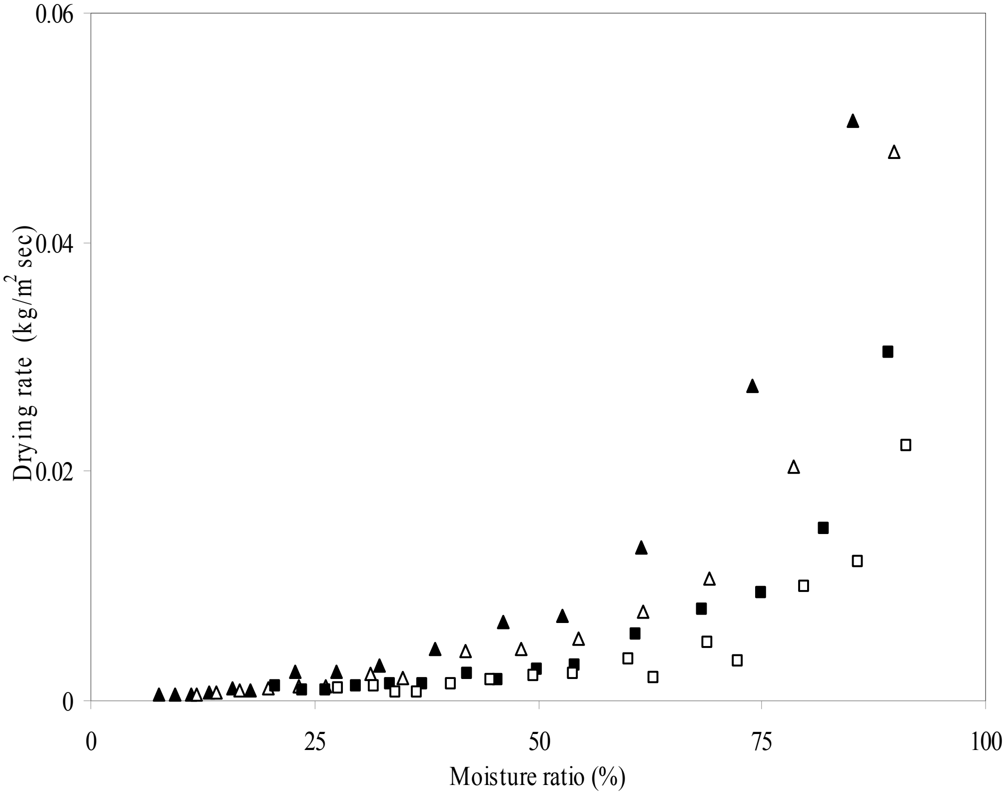


**Fig. 2. Effect of drying rate on various sample thicknesses at microwave output powers of 180 W and initial moisture content 80 % (▲, 11mm; △, 12 mm; ■, 13 mm; □, 14 mm ).**

## 3.2 Effective moisture diffusivity:

The effective moisture diffusivity of a material characterizes its intrinsic mass transfer property of moisture in the sample. The mechanism of movement/removal of moisture from interior to the surface of plaster of paris during the microwave operation was only due to diffusivity as explained by Fick's second law. Since the moisture movement mechanism inside the sample is a highly complicated process and very limited information are available (Abe and Afzal, 1997). The effective moisture diffusivity (which is affected by composition, moisture content, temperature, and porosity of the material) was used to explain the mechanism of moisture movement during drying process.

**Table 4. Statistical analysis of the models at various sample thicknesses (Condition : Initial moisture content 80%, Microwave output power : 180W)**

| Sl. No | Model Name | Sample thickness (m) | Modeling efficiency | RMSE | RSS |
|---|---|---|---|---|---|
| 1 | Newton | 0.011 | 0.99755 | 0.00905 | $8.20\times10^{-05}$ |
| | | 0.012 | 0.99707 | 0.01005 | 0.00010 |
| | | 0.013 | 0.99668 | 0.01230 | 0.00015 |
| | | 0.014 | 0.99436 | 0.02344 | 0.00054 |
| 2 | Page | 0.011 | 0.99755 | 0.00905 | $8.2\times10^{-05}$ |
| | | 0.012 | 0.99707 | 0.01005 | 0.00010 |
| | | 0.013 | 0.99668 | 0.01230 | 0.00015 |
| | | 0.014 | 0.99436 | 0.02344 | 0.00055 |
| 3 | Henderson | 0.011 | 0.99820 | 0.00833 | $6.95\times10^{-05}$ |
| | | 0.012 | 0.99776 | 0.00871 | $7.59\times10^{-05}$ |
| | | 0.013 | 0.99689 | 0.01215 | 0.00014 |
| | | 0.014 | 0.99539 | 0.02211 | 0.00048 |
| 4 | Logarithmic | 0.011 | 0.99791 | 0.00656 | $4.3\times10^{-05}$ |
| | | 0.012 | 0.99797 | 0.01068 | 0.000114 |
| | | 0.013 | 0.99933 | 0.00756 | $5.72\times10^{-05}$ |
| | | 0.014 | 0.99924 | 0.00977 | $9.56\times10^{-05}$ |
| 5 | Wang and Singh | 0.011 | 0.98960 | 0.02046 | 0.00041 |
| | | 0.012 | 0.99498 | 0.01643 | 0.00027 |
| | | 0.013 | 0.99771 | 0.01389 | 0.00019 |
| | | 0.014 | 0.99923 | 0.01201 | 0.00014 |
| 6 | Diffusion | 0.011 | 0.99436 | 0.02344 | 0.00549 |
| | | 0.012 | 0.99614 | 0.03875 | 0.00150 |
| | | 0.013 | 0.99657 | 0.01843 | 0.00033 |
| | | 0.014 | 0.99709 | 0.01128 | 0.00012 |
| 7 | Verma | 0.011 | 0.99868 | 0.00756 | $5.73\times10^{-05}$ |
| | | 0.012 | 0.99818 | 0.00750 | $5.64\times10^{-05}$ |
| | | 0.013 | 0.99701 | 0.01206 | 0.00014 |
| | | 0.014 | 0.99588 | 0.02136 | 0.00045 |
| 8 | Two Term Exponential | 0.011 | 0.99755 | 0.00905 | $8.2\times10^{-05}$ |
| | | 0.012 | 0.99707 | 0.01005 | 0.00010 |
| | | 0.013 | 0.99668 | 0.01230 | 0.00015 |
| | | 0.014 | 0.99436 | 0.02344 | 0.00055 |
| 9 | Midilli | 0.011 | 0.99994 | 0.00599 | $3.59\times10^{-05}$ |
| | | 0.012 | 0.99978 | 0.00711 | $5.06\times10^{-05}$ |
| | | 0.013 | 0.99962 | 0.00650 | $4.23\times10^{-05}$ |
| | | 0.014 | 0.99916 | 0.00925 | $8.57\times10^{-05}$ |

**Table 5. The estimated parameters of model equations at various sample thicknesses (Condition : Initial moisture content 80%, Microwave output power : 180W)**

| Model name | Sample thickness (m) | Constants | | | |
|---|---|---|---|---|---|
| | | k | n | a | b |
| Midilli | 0.011 | 0.00648 | 1.04431 | 0.99656 | $-5.9\times10^{-06}$ |
| | 0.012 | 0.00581 | 1.01613 | 1.00429 | $-4.5\times10^{-05}$ |
| | 0.013 | 0.00503 | 0.92613 | 0.99882 | -0.00032 |
| | 0.014 | 0.00439 | 0.89384 | 0.99674 | -0.00078 |

The following assumptions were made: The molded and tempered rectangular plaster of paris cuboids were assumed as a slab ( since, the height is small when compared with length and breath); Moisture is initially uniformly distributed throughout the mass of a sample; Mass transfer is symmetric with respect to the center, Surface moisture content of the sample instantaneously reaches equilibrium with the condition of surrounding air, Resistance to mass transfer at the surface is negligible, when compared to internal resistance of the sample, Mass transfer follows diffusion mechanism, and shrinkage is negligible. Based on these assumptions, the effective moisture diffusivity could be estimated as suggested by Crank (**1995**):

$$MR = \frac{8}{\pi^2}\exp\left[-\frac{\left(D_{eff}.\pi^2\right)}{T^2}t\right] \qquad (6)$$

Which, could be further simplified (Nuh and Brinkworth, 1997; Pala et al., 1996) to a straight-line relation as:

$$\ln\left(MR\right) = \ln\left[\frac{8}{\pi^2}\right] - \left[\frac{\left(D_{eff}.\pi^2\right)}{T^2}\right].t \qquad (7)$$

The effective moisture diffusivities are determined by typically plotting the linear relationship between ln(MR) and drying time for various microwave output powers and initial moisture content.

Effective moisture diffusivity, which describes all the possible mechanisms of moisture movement, includes liquid diffusion, vapor diffusion, surface diffusion, Knudsen diffusion, capillary flow and hydrodynamic flow can be estimated from drying curves either by the regular regime technique or the slope method (Suk and Sad, 1995).

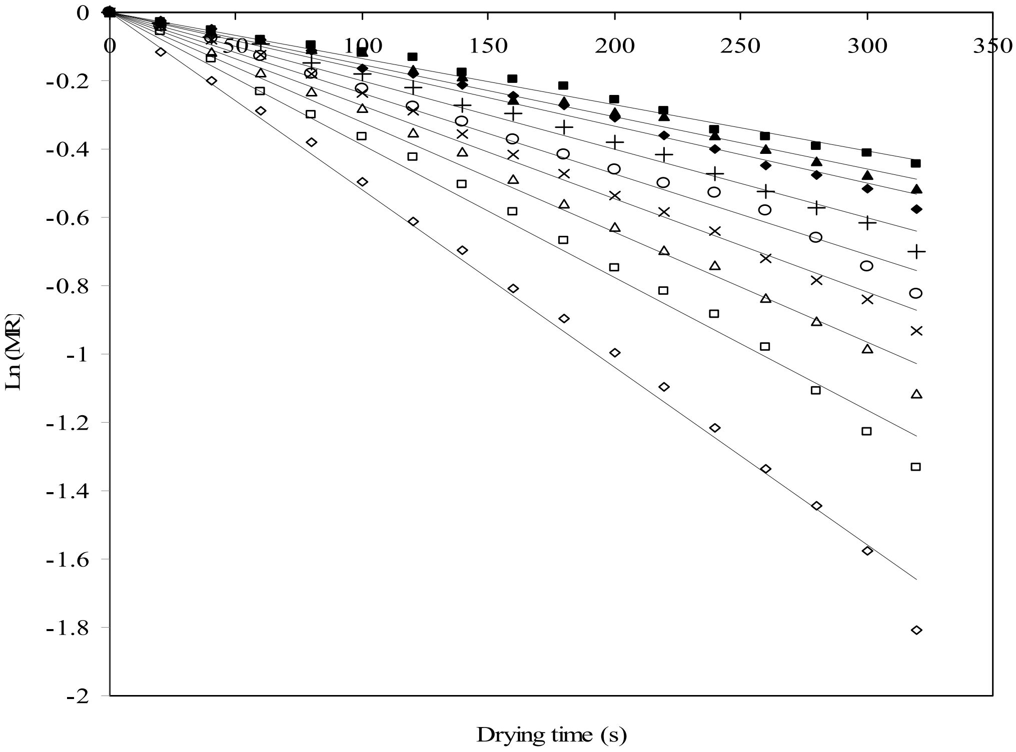


**Fig. 3.** **Drying kinetic relationship of plaster of paris at different microwave power ranges for 13 mm sample thickness: ◊ - 180 W, IM 80%; □, 360 W, IM 80%; ∆, 180 W, IM 75%; ×, 180 W, IM 70%; ○, 360 W, IM 75%; +, 540 W, IM 75%; ♦, 540 W, IM 80%; ▲, 360 W, IM 70%; ■, 540 W, IM 70%.**

DOI: 10.2202/1934-2659.1316

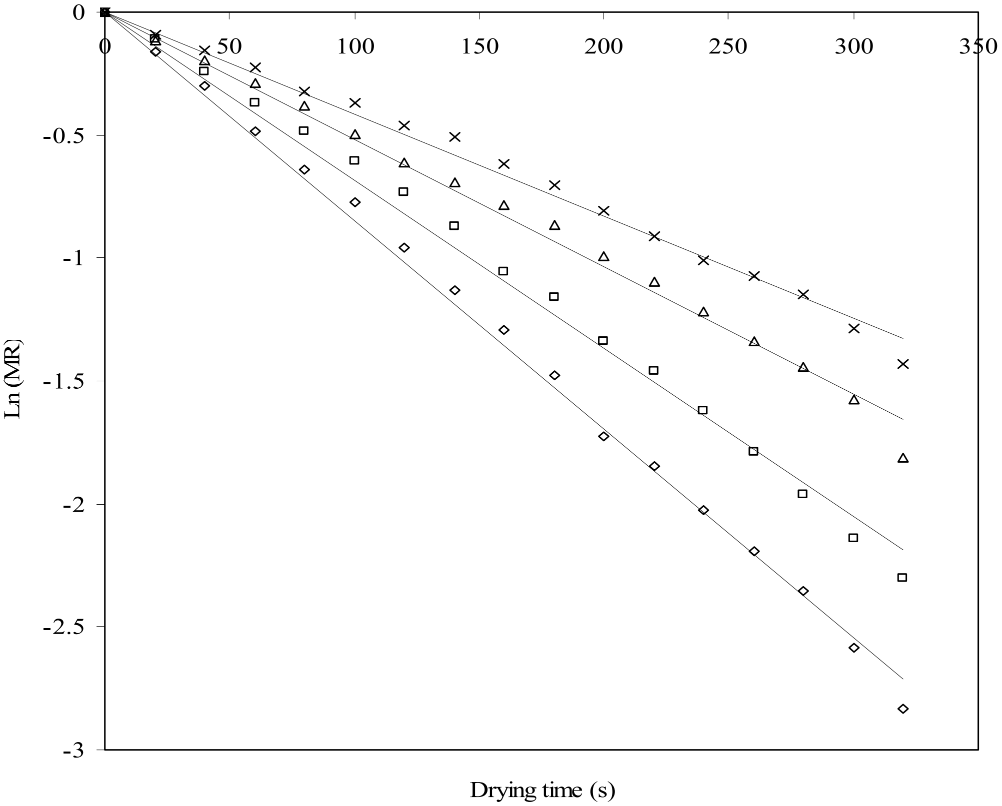


**Fig. 4. Drying kinetic relationship of plaster of paris at different sample thickness for microwave power 180 W and IM 80. ◊, 14 mm; □, 13mm; Δ, 12mm; ×, 11mm.**

As suggested by Karathanos et al. (1990), the method of slopes was used in which the slopes of the graph (Fig. 3 and Fig.4) for different microwave output powers (540, 360 and 180W), initial moisture content of sample (70, 75 and 80 %) and sample thicknesses (11,12,13 and 14mm), were used to calculate the effective moisture diffusivity. The details of effective moisture diffusivity values ($D_{eff}$) and the corresponding values of coefficients of determination $R^2$ of Eqn. 7 are presented in Table 6 and Table 7. The presence of maximum moisture content in samples responded quantitatively faster to microwaves resulting in immediate and complete drying of plaster of paris (Sabarez et al., 1997).

**Table 6 The estimated effective moisture diffusivity values and statistical analysis of linear model at various microwave output powers for sample thicknesses of 0.013m.**

| Sl no | Moisture content | Power output | Slope x$10^3$ | $D_{eff}$ x $10^8$ ($m^{2}\cdot s^{-1}$) | $R^2$ |
|---|---|---|---|---|---|
| 1 | 80 | 180 | 5.187 | 2.218 | 0.9929 |
| 2 | 80 | 360 | 3.872 | 1.656 | 0.9910 |
| 3 | 75 | 180 | 3.209 | 1.372 | 0.9909 |
| 4 | 70 | 180 | 2.727 | 1.166 | 0.9902 |
| 5 | 75 | 360 | 2.359 | 1.009 | 0.9894 |
| 6 | 75 | 540 | 2.002 | 0.856 | 0.9891 |
| 7 | 80 | 540 | 1.665 | 0.712 | 0.9877 |
| 8 | 70 | 360 | 1.519 | 0.650 | 0.9875 |
| 9 | 70 | 540 | 1.347 | 0.576 | 0.9876 |

**Table 7 The estimated effective moisture diffusivity values and statistical analysis of linear model at uniform microwave output power of 180W and initial moisture content of 80% for varied sample thicknesses.**

| Sl no | Sample thickness(m) | Slope x$10^3$ | $D_{eff}$ x $10^8$ ($m^{2}\cdot s^{-1}$) | $R^2$ |
|---|---|---|---|---|
| 1 | 0.011 | 8.47 | 2.6927 | 0.9967 |
| 2 | 0.012 | 6.84 | 2.5429 | 0.9928 |
| 3 | 0.013 | 5.17 | 2.1014 | 0.9919 |
| 4 | 0.014 | 4.15 | 1.9187 | 0.9915 |

## 3.3 Activation energy:

The temperature within/inside the sample is not a measurable variable in the standard microwave oven used for drying process. The Arrhenius type of equation was used in a tailored form to illustrate the relationship between the diffusivity coefficient and the ratio of the microwave output power to sample thickness instead of the temperature, for calculation of the activation energy. The dependency of effective moisture diffusivity $D_{eff}$ , on the ratio of microwave output power to sample thickness was suggested by Dadali et al.(2007),

$$D_{eff} = D_0 \exp\left[\frac{-E_a.q}{P}\right] \tag{8}$$

The activation energies involved in microwave drying of plaster of paris, under different drying conditions, were estimated from the slopes of the curve plotted according to Eqn. 8, which was 22.1($W.mm^{-1}$), while the pre-exponential factor resumed to be 1.059 x $10^{-7}$ $m^2$. $s^{-1}$ (Fig.5).

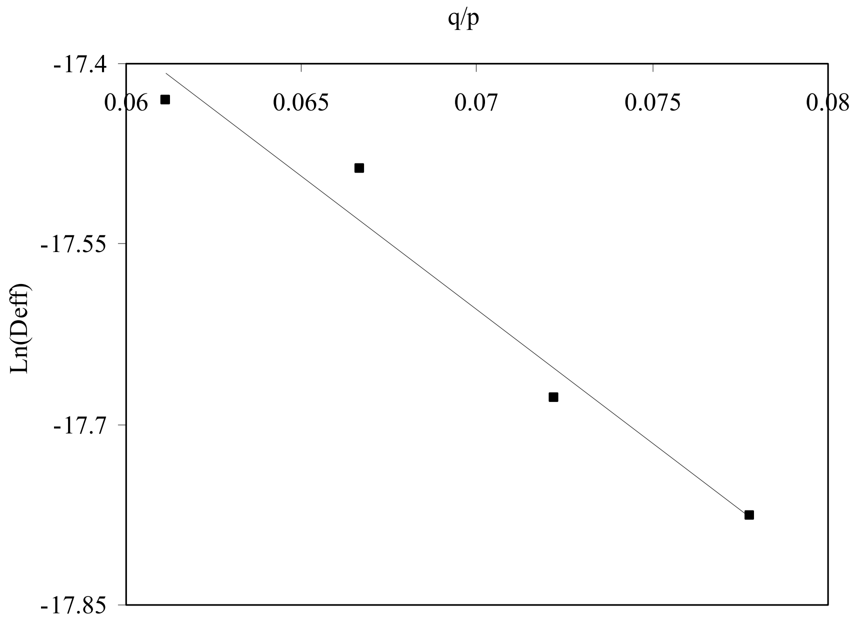


**Fig. 5. The effect of sample thickness/ power on effective moisture diffusivity for microwave drying of plaster of paris; (■ calculated data, — model).**

To validate the correlation between the effective moisture diffusivity and the kinetic rate constant on drying, the following Arrhenius-type exponential relationship was employed (Eqn. 9). The dependency of the effective moisture diffusivity on the ratio of microwave output power to sample thickness was represented in a straight line equation.

$$k = k_0 \exp\left[\frac{-E_a.q}{P}\right] \qquad (9)$$

Where, k is the drying rate constant obtained by using Midilli's model ($\text{min}^{-1}$), $k_0$ is the pre-exponential constant ($\text{min}^{-1}$). The above equation could be simplified to a straight-line equation as

$$\ln k = \ln k_0 - E_a\left[\frac{q}{P}\right] \qquad (10)$$

The values of $k_0$ and $E_a$ were estimated as 0.0277 $\text{min}^{-1}$ and 23.62W.$\text{mm}^{-1}$, respectively. The fitness of the data with the model was illustrated in Fig. 6.

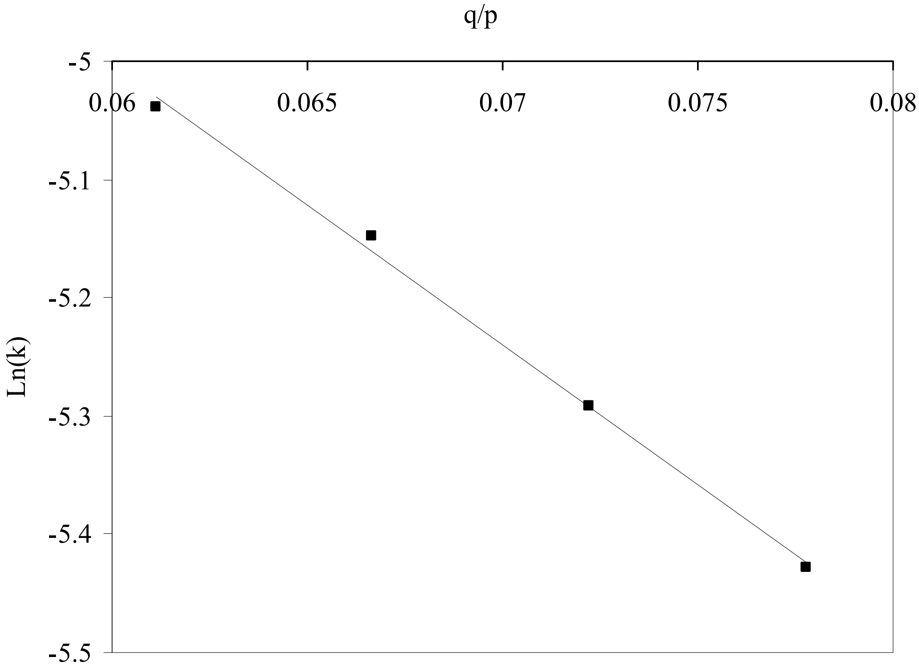
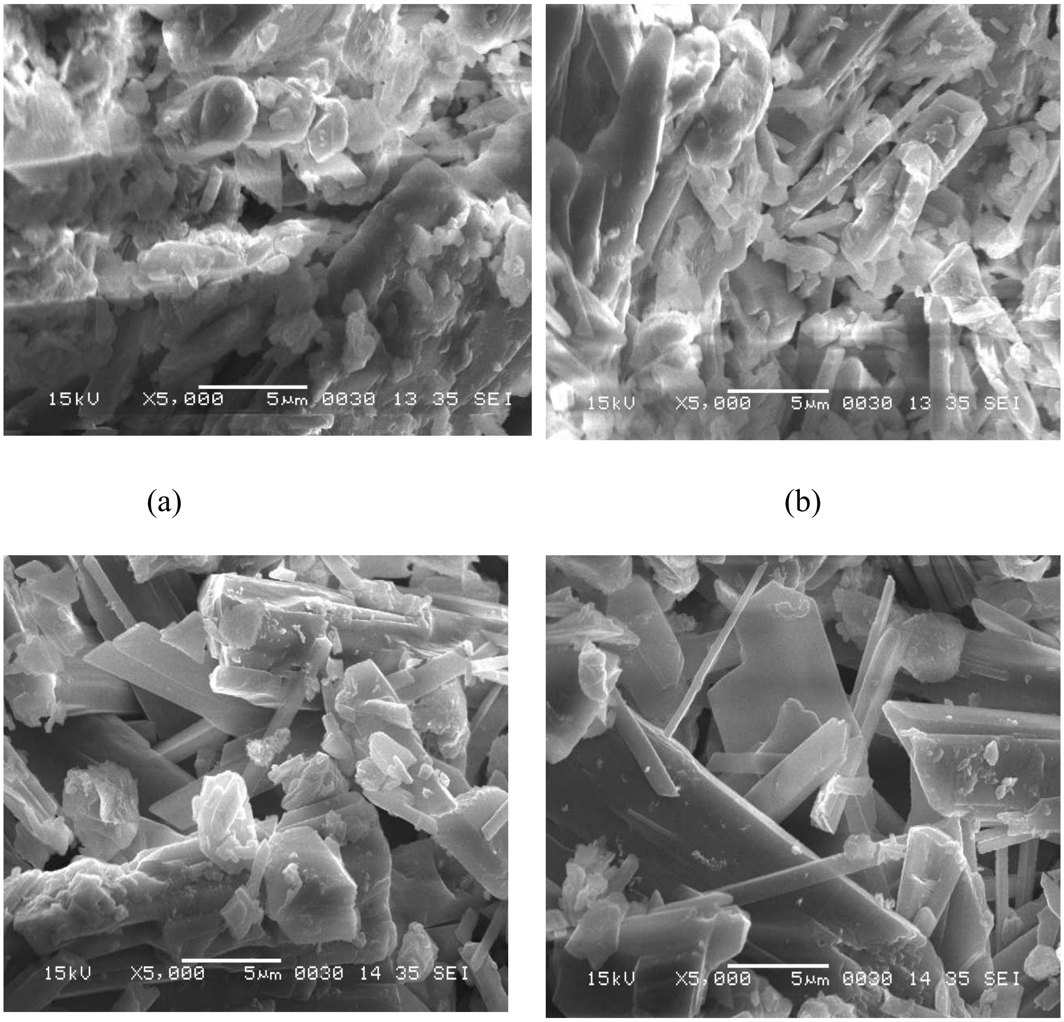


**Fig. 6. The effect of sample thickness/ power on drying rate constant for microwave drying of plaster of paris ; ( ■ calculated data, — model).**

## 3.4 Microstructure determination:

The internal heat generation influences the heat and mass transfer effects on samples in external as well as internal characteristics of plaster. Porosity has a well-defined effect on the physical properties, such as mass diffusion coefficient, thermal conductivity, and thermal diffusivity during drying process. Therefore, the information on porosity is needed for the estimation of the physical, mechanical, electrical and chemical properties, and characterizing the quality of a product. The material when subjected to microwave irradiation, losses some of the volatile matter and moisture content. The dried plaster of paris contains numerous pores within it, forming an open structure (Van Arsdel et al., 1973; Wang and Brennan, 1995). Microwave causes violent evaporation of water in pores followed by a collapse of porous structure and partial disconnection of pores.



(a) (b)

(c) (d)

**Fig. 7. Scanning electron micrographs of dried plaster of paris cuboids : (a) 14mm thickness, (b) 13mm thickness, (c) 12mm thickness and (d) 11mm thickness.**

SEM micrographs (Fig 7) showed that the sample was almost fully dense with large grains in the central part. Thin hairline cracks were observed on the surface of the material. The grain size was smaller in magnitude at the surface than at the centre of the specimen. Porosity is strongly affected by the drying method and conditions, an increase in porosity was observed for the materials dried. Microwave irradiation is a process by which, the inherent moisture content of any material can be reduced, the movement of the water molecules is from the centre of the material to the outer surface, and this creates an increased porous microstructure in the irradiated material. The enhanced porosity is observed to be the key factor that improves the drying rate of plaster of paris.

### 3.5 Determination of the energy performance and efficiency of microwave drying:

Specific unit energy consumption ($Q_s$), defined as energy required for evaporating water from the plaster of paris ($MJkg^{-1}$), was used to describe the energy consumption during drying.

$$Q_S = \left[ \frac{(t_{on})(P)(1 + X_o)}{(M_i)(X_o - X_f)} \right] \tag{11}$$

The estimated specific unit energy consumption values ( Eqn.11) are found to depend on the power supplied by the oven, initial moisture of sample and the drying time. In this study, energy consumptions for 180 W microwave output power level (80% initial moisture content) was found to be 0.4557 $MJkg^{-1}$, while it raised up to 2.6447 $MJkg^{-1}$ for higher powers of 540W (Table 8). Different microwave drying scenarios, under the same power output (180 W), were performed to investigate the effects of moisture contents and drying times on the microwave drying efficiencies ($\eta_d$) as,

$$\eta_d = \left[ \frac{(m_w)(\lambda_w)}{(P\Delta t_{on})}(100) \right] \tag{12}$$

Where $m_w$ is the mass of water evaporated (kg), $\lambda_w$ is the latent heat of vaporization of water (2260 KJ. $kg^{-1}$). The results shown in Table 9 indicated that under the same microwave output power the sample thicknesses play an important role in energy consumption and microwave drying efficiency. While the sample thickness remained at 11 mm, the specific unit energy consumption was 0.4189 $MJkg^{-1}$, whereas it increased to 0.4732 $MJkg^{-1}$, for a thickness of 14mm., while microwave drying efficiency decreased from 90.00% to 77.89%., while thickness of sample increased.

**Table 8. Specific Unit Energy Consumption for drying Plaster of paris at different Initial Moisture content, Microwave Power output and uniform sample thicknesses of 0.013m and constant drying time of 320 sec.**

| Sl. No | Microwave power output (MJ/S) | Initial weight (Kg) | Initial moisture content (%) | Final moisture content (%) | Specific unit energy consumption ($MJ.Kg^{-1}$) | Microwave drying efficiency (%) |
|---|---|---|---|---|---|---|
| 1 | 0.000180 | 0.153 | 80.80 | 13.23 | 0.4557 | 82.56075 |
| 2 | 0.000360 | 0.147 | 79.43 | 21.00 | 1.0787 | 41.10405 |
| 3 | 0.000180 | 0.132 | 74.11 | 24.27 | 0.6576 | 72.88229 |
| 4 | 0.000180 | 0.118 | 70.06 | 29.56 | 0.8564 | 68.80715 |
| 5 | 0.000360 | 0.135 | 74.29 | 32.57 | 1.5399 | 34.22725 |
| 6 | 0.000540 | 0.128 | 74.42 | 36.93 | 2.7158 | 22.07367 |
| 7 | 0.000540 | 0.151 | 81.83 | 45.99 | 2.6447 | 21.24689 |
| 8 | 0.000360 | 0.122 | 70.15 | 41.87 | 2.3756 | 30.36762 |
| 9 | 0.000540 | 0.120 | 70.43 | 45.22 | 4.0800 | 20.21896 |

**Table 9 Specific Unit Energy Consumption for drying Plaster of paris at uniform Initial Moisture content (80%), Microwave Power output (0.000180 KJ/S), drying time (320 S) and varied sample thicknesses.**

| Sl. No | Sample thickness (mm) | Initial weight (Kg) | Initial moisture content (%) | Final moisture content (%) | Specific unit energy consumption ($MJ.Kg^{-1}$) | Microwave drying efficiency (%) |
|---|---|---|---|---|---|---|
| 1 | 11 | 0.141 | 79.98 | 6.25 | 0.4189 | 90.00 |
| 2 | 12 | 0.147 | 79.36 | 7.96 | 0.4237 | 86.91 |
| 3 | 13 | 0.153 | 80.80 | 13.23 | 0.4557 | 82.56 |
| 4 | 14 | 0.162 | 80.22 | 19.20 | 0.4732 | 77.85 |

## 4. Conclusion

The microwave drying of the plaster of paris was performed at different conditions and the moister ratio obtained through the experiments were fitted to the various thin-layer models available in the literature. From the statistical analysis of the models, it was found that the Midilli model well represents the experimental data. Further the drying rate constant (Table 5) was correlated with effective moisture diffusivity for different initial moisture contents (Table 6) and thickness (Table 7) of the sample. Also the activation energy for the microwave drying process was found through the effective moisture diffusivity and drying rate constant at different conditions and the values are 22.1 $W.mm^{-1}$ and 23.62$W.mm^{-1}$ respectively. The specific unit energy consumption was estimated for different operation conditions.

## Nomenclature

a,b,k,n : Empirical coefficients in models,
$k_0$ : Pre-exponential constant ($min^{-1}$),
q : Thickness of sample (mm).
t : Drying time (s)
$t_{on}$ : Total drying time (s),
D : Depth of microwave cavity (mm)
$D_{eff}$ : Effective moisture diffusivity ($m^2.s^{-1}$),
H : Height of microwave cavity (mm),
$E_a$ : Activation energy ($W.mm^{-1}$),
$M_i$ : Initial mass of sample (kg)
P : Microwave power output (W),
T : Half of thickness of sample (mm)
W : Width of microwave cavity (mm)
X : Moisture content at time t (kg $kg^{-1}$, dry solid).
$X_c$ : Equilibrium moisture content, (kg $kg^{-1}$, dry solid),
$X_f$ : Final moisture content, (kg $kg^{-1}$, dry solid),
$X_0$ : Initial moisture content (kg $kg^{-1}$, dry solid),
Qs : Specific energy consumption (MJ $kg^{-1}$),
$\acute{\eta}_d$ : Microwave drying efficiency (%),
$\lambda_w$ : Latent heat of vaporization of water (J $kg^{-1}$)

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