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An Empirical Model for the Estimation of Moisture Ratio During Microwave Drying of Plaster of Paris

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The drying characteristics of plaster of Paris (POP) under microwave irradiation were studied for different shapes of materials through various drying parameters like microwave power, initial moisture content, and drying time. An empirical model for the estimation of moisture ratio was developed using the drying kinetic data of POP. Further, the experimental data on moisture ratio of POP for different operating conditions were fitted with the nine basic drying model equations. Based on the observations, the constants and coefficients of the literature models were rewritten in the form of Arrhenius and logarithmic expressions considering microwave power as input variable. Fifty-eight new model expressions were derived by changing the constants and coefficients and tested using the present experimental data. From the analysis of RMSE, χ^2, and EF parameters for the derived models, a suitable empirical model (Model No. 55, RMSE = 0.0874; χ^2 = 0.0020; EF = 0.9999) was established to represent the present experimental data on microwave drying of POP.

Keywords Characterization; Empirical model; Microwave drying; Plaster of Paris (POP)

INTRODUCTION

Plaster of Paris (POP) is a dry, fine, white powder building material similar to mortar or cement, based on calcium sulfate ($CaSO_4\ 1/2H_2O$). Plaster of Paris is prepared through partial dehydration reaction by heating calcium sulfate dihydrate to 120–180°C (Eq. (1)). The partially dehydrated mineral is called calcium sulfate hemihydrate or calcined gypsum, commonly known as plaster. When the dry POP powder is mixed with water at normal (ambient) temperature, it rapidly reverts to the preferred dihydrate form, into sheets of Ca^{2+} and SO_4^{2-} ions held together by hydrogen bonds in the water molecules, while physically setting to form a rigid and relatively strong gypsum crystal lattice at 380°C (Eq. (2)).

$$CaSO_4 \cdot 2H_2O + \text{Heat} \longrightarrow CaSO_4 \cdot \frac{1}{2}H_2O + 1\frac{1}{2}H_2O(\text{steam}) \tag{1}$$

$$CaSO_4 \cdot \frac{1}{2}H_2O + 1\frac{1}{2}H_2O \longrightarrow CaSO_4 \cdot 2H_2O \tag{2}$$

It re-forms into gypsum, initially as a paste but eventually hardening into a solid. Unlike other ceramic materials, plaster remains quite soft after drying. 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. The microstructure of hardened gypsum paste affects most of the physical and engineering properties, particularly its rigidity. POP, known for its porosity and strength, is used as fire resistance on residential and other structures, cast into various shapes including sheets, sticks, and molds (to immobilize metal casting), when mixed with polymers. POP is used as a bone repair cement, where small amounts of calcined gypsum are added to earth to create strong structures directly from cast earth, an alternative to adobe (which loses its strength when wet). The conditions of moisture removal can be changed to adjust the porosity of the hemihydrate, resulting in the formation of alpha and beta hemihydrates, which are chemically identical. Several drying methods are commercially available and the selection of the optimal method for drying is determined by the quality requirements, raw material characteristics, and economic factors.

Advances in the drying technology of porous material have been increasingly stimulated over the past few years in contrast to the traditional convective drying with hot air (solar drying, open air drying, single layer solar drying,

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convective type tray dryer, etc.) and are becoming more important. The use of microwaves as a source of energy is rapidly growing and has a convenient advantage over other conventional processes for drying. Microwave irradiation technology has already been successfully exploited to industrial and domestic applications. Currently these applications have also been extended to the field of medical sciences and environmental organic pollution for polycyclic aromatic hydrocarbons (PAHs),[1–3] polychlorinated biphenyls (PCBs),[4] etc.

Due to the advantage of internal and volumetric heating properties (dipole rotation and/or ionic conduction), thermal gradients during microwave processing are avoided that provide a uniform environment for reaction. The use of microwave rays in the drying of products has become widespread because it minimizes the decline in quality and provides an effective and rapid heat distribution in the material. Furthermore, high-quality product is obtained via microwave drying in addition to the reduction in drying period and energy conservation during drying.[5] Therefore, microwave heating has shown advantages over the conventional heating method in terms of energy efficiency, higher rate of heating, and reduction in heating time.[6] Industrial and geochemical interest has resulted in a considerable amount of research on the mechanism of POP crystal growth, both in the presence/absence of different types of chemical additives.[7] Further, the overall picture of dehydration characteristics, the mechanism of their hydration and the crystal growth, the role of the size and stability of critical nuclei, and the different crystal faces and step edges of POP have been discussed in the literature.[8] Few studies deal with the possibility of predicting the rate of heating up of the material exposed to microwaves, while others are concerned with the specific acceleration of drying processes by means of microwaves.

Mathematical models are necessary to analyze, simulate, and design and scale up the microwave drying process for commercial applications. The complexity of an appropriate model depends on its purpose. Dynamic simulation requires more comprehensive models, while simple models meet the requirements of designing or presenting the technical calculation. The comprehensive models mentioned in the above-mentioned literatures are generally complex and more time consuming than the latter. Both categories of models (comprehensive and simple) require the understanding of the drying kinetics before designing a drying process. The models provide the basic information for a designer to choose the technique and drying devices to obtain a good quality product with the least possible energy consumption. Investigators show greater importance in developing new models particularly for food materials, including drying parameters like air velocity and drying temperature for apricot,[9,10] grape,[11–13] green paper, pumpkin, green bean, and onion,[14] eggplant,[15] sweet potato,[16] rough rice,[17] carrot,[18,19] mushroom and pollen,[20] barley,[21] pistachio,[22,23] apricot, peaches, figs, and plum.[24] In general, these attempts are performed to obtain the best model from the basic models by analyzing the basic models with their experimental data (change of moisture ratio with time) and the constants or coefficients of the selected model were further modified by a relationship that had basic function of the drying parameter as drying temperature, air velocity, etc. The results of these models, which correspond to the restricted experimental output of the individual investigators using their own materials, still leave enough room for further improvement in the field of drying kinetics. Furthermore, the microwave drying process of POP has not been well investigated. Therefore, in the current study, the microwave drying of POP was performed to develop a new suitable model to represent the effects of drying time and microwave output power on the moisture removal rate.

MATERIALS AND METHODS

Sample Preparation

The commercially available high-purity, analar grade POP ($< 50\,\mu m$) was obtained from SRL, India. POP was then made into paste with carrier water and molded to three different basic geometries, including square-faced cuboids ($70 \times 70 \times 15$, $L \times B \times H$ in mm), rectangular-faced cuboids ($80 \times 70 \times 13$, $L \times B \times H$ in mm), and cylinders (64×18, $D \times H$ in mm) weighing approximately 150 g. The samples were prepared having an approximate initial moisture content of 70–80% by adding required amount of water with POP, making a paste of POP. Freshly molded samples were initially tempered for a period of 18 to 24 h (resting period) to improve the rigidity and stability of the material.[25] After tempering, the prepared samples were used for the microwave drying experiments.

Microwave Drying

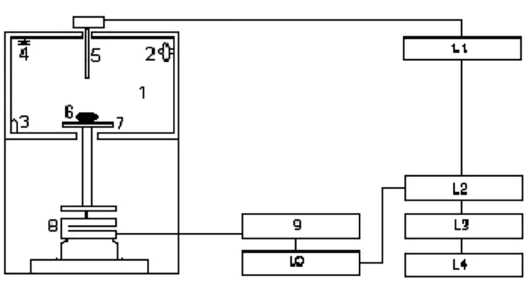
The commercial microwave-drying oven (SAMSUNG C-103F model) was modified for the present experimental study, with an inbuilt bioceramic cavity ($352 \times 220 \times 300$, $W \times H \times D$ in mm). The microwave generator at 2450 MHz provided a continuous supply of the microwave output nominal power at a controllable level ranging from 100 to 900 watts with increments. The oven is provided with a magnetron for producing dielectric waves and a fluorescent bulb and a circulating fan were fixed for the distribution of the produced microwave. An inbuilt weighing system was used to monitor the sample weight loss with drying time,[26] which consisted of a weighing beam (quartz) and load cell (sensitivity ± 0.01 g). A circular opening with a diameter of 25 mm was drilled at the bottom of the oven cavity, through which the weighing beam was introduced to hold the sample at its top. The bottom of the beam was placed in the load cell (sensitivity ± 0.01 g) to measure the load placed on top of the weighing beam, and the load cell was connected to the digital converter through a recorder. Further, the digital converter was connected to the workstation to convert the digital data into graphical format. At any time the weight of the sample was shown on the digital screen available at the drying equipment. Software was developed and programmed for the current requirements. Proper microwave leak-proof agents were provided at the bottom of the cavity where the hole was drilled. The schematic diagram of the present experimental setup is shown in Fig. 1.

Experimental Procedure

All experiments were conducted at three different initial moisture contents (approximately 70, 75, and 80%), power ranges (180, 360, and 540 W), and geometry (square, rectangle, and cylinder). The mass of the samples chosen for the runs was approximately 150 g. The prepared samples were then exposed to the microwave irradiation region for a specific time period and the weight loss corresponding to the time intervals was noted. The microwave-dried samples were then placed in a hot air oven at 105°C until bone dry and the weights of the sample were noted. The list of experiments conducted along with the range of variables covered are given in Table 1. All experiments were performed in triplicate, and the average values of these replications were used for further analysis of microwave drying parameters like drying rate and moisture content at different drying times.

Mathematical Modeling of Microwave Drying Curves

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



1. Microwave Cavity
2. Magnetron
3. Fluorescent light bulb
4. Circulating fan
5. Thermocouple
6. Sample
7. Sample holder
8. Weighing Beam
9. Weighing recorder
10. Voltmeter

L1. Temperature recorder
L2. Digital converter
L3. Data Acquition Card
L4. Computer

FIG. 1. Schematic diagram of the microwave drying experimental setup.

material being dried and the equilibrium moisture content at the drying conditions. Mathematically, this can be written in terms of moisture ratio (MR), which is as follows:

$$MR = [(X - X_c)/(X_o - X_c)] \tag{3}$$

Hence, the drying process was employed with microwaves, and the equilibrium moisture content, X_c, was assumed to be zero. The moisture ratio (MR) was simplified to X/X_0 instead of $[(X - X_c)/(X_0 - X_c)]$. The obtained microwave drying curves were analyzed using nine different empirical and semiempirical drying models[27–44] (Table 2) through regression analyses. Average regression coefficient (r_{avg}) is the primary criterion for selecting the best equation to describe the current microwave drying curves obtained for POP. The constants and coefficients of these equations are further described with various types of expressions like Arrhenius, logarithmic, linear, exponential, and power type in terms of temperature.[15] Since the temperature inside the chamber directly depends on the power input to the system, all the expressions were derived in terms of power in the current research.

$$\text{Arrhenius type} = a \exp(-b/8.314\ P)$$

$$\text{Logarithmic type} = ab \ln(P)$$

$$\text{Linear type} = abP$$

$$\text{Exponential type} = a \exp(bP)$$

$$\text{Power type} = aP^b$$

A suitable mathematical model to represent the effect of power on the constants and coefficients was investigated by using multiple combinations of different equations using Arrhenius and logarithmic type expressions.[45] All nine models shown in Table 2 can be derived in to m^n number of new models, where n is the total number of constants and coefficients in the model and m is the number of combination equations. Fifty-eight new equations were derived as detailed in Table 3 and the regression analyses were performed using all the equations individually.

The root mean square error (RMSE), residual sum of squares (RSS), and modeling efficiency (EF) were used as the primary criteria to select the best equation to account for variation in the drying curves of the dried samples.[13,39,46] The RMSE gives the deviation between the predicted and experimental values and is required to reach zero. The EF also gives the ability of the model and its highest value is 1. These statistical values can be calculated as follows:

$$RMSE = \left[(1/2)\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i})^2\right]^{0.5} \tag{4}$$

$$RSS = \sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i})^2 \tag{5}$$

TABLE 1
Summary of experiments for drying plaster of Paris

Exp. No.	Microwave power (W)	Initial moisture content (%)	Sample geometry	Surface area (m^2)	Depth (m)
1	180	70	Square	0.0091	0.015
2	360				
3	540				
4	180	75			
5	360				
6	540				
7	180	80			
8	360				
9	540				
10	180	70	Rectangle	0.0095	0.013
11	360				
12	540				
13	180	75			
14	360				
15	540				
16	180	80			
17	360				
18	540				
19	180	70	Cylinder	0.0068	0.018
20	360				
21	540				
22	180	75			
23	360				
24	540				
25	180	80			
26	360				
27	540				

$$EF = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{\exp,avg})^2 - \sum_{i=1}^{N}(MR_{pre,i} - MR_{\exp,i})^2}{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{\exp,avg})^2} \quad (6)$$

where $MR_{\exp,i}$ is the ith experimental moisture ratio; $MR_{\text{pred},i}$ is the ith predicted moisture ratio; n is the number of constants in drying model; and $MR_{\exp,\text{avg}}$ is the average value of experimental moisture ratio.[9,10,23,47,48] These statistical parameters have been widely used as a primary criterion

TABLE 2
Mathematical models given by various authors tested for the moisture ratio values of POP

No.	Model name	Equation	References
1	Newton	$MR = \exp(-kt)$	[27–29,46]
2	Page	$MR = \exp(-kt^n)$	[30–33]
3	Henderson	$MR = a\exp(-kt)$	[4,34–36]
4	Logarithmic	$MR = a\exp(-kt) + c$	[3,37,38]
5	Wang and Singh	$MR = 1 + at + bt^2$	[39,40]
6	Diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	[14,41]
7	Verma	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	[42]
8	Two-term exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	[43]
9	Midilli	$MR = a\exp(-k[t^n] + bt)$	[44]

TABLE 3
Mathematical models derived from basic equations from Table 2

Model no.	Arrhenius Logarithmic	$\{a \exp[-b/(8.314P)]\}$ $(\mathrm{a}+\mathrm{b} \ln[\mathrm{P}])$
Newton: $MR = \exp(-kt)$		
1	$\exp(-\{a \exp[-a_1/(8.314P)]\}\ t)$	
2	$\exp\{-[a+a_1 \ln(P)]\ t\}$	
Page: $MR = \exp(-kt^n)$		
3	$\exp(-\{a \exp[-a_1/(8.314P)]\}\ t_1^{[n \exp[-n/(8.314P)]]})$	
4	$\exp(-\{a \exp[-a_1/(8.314P)]\}\ t_1^{[n+n \ln(P)]})$	
5	$\exp\{-[a+a_1 \ln(P)]\ t_1^{\{n \exp[-n/(8.314P)]\}}\}$	
6	$\exp\{-[a+a_1 \ln(P)]\ t_1^{[n+n \ln(P)]}\}$	
Henderson: $MR = a \exp(-kt)$		
7	$[a \exp[-a_1/(8.314P)]\exp(-\{k \exp[-k_1/(8.314P)]\}t)]$	
8	$\{a \exp[-a_1/(8.314P)]\}\ \exp\{-[k+k_1 \ln(P)]\ t\}$	
9	$[a+a_1 \ln(\mathrm{P})]\ \exp(-\{k \exp[-k_1/(8.314P)]\}t)$	
10	$[a+a_1 \ln(P)]\ \exp\{-[k+k_1 \ln(P)]\ t\}$	
Logarithmic: $MR = a \exp(-kt)+c$		
11	$\{a \exp[-a_1/(8.314P)]\}\ \exp(-\{k \exp[-k_1/(8.314P)]\}\ t)+\{c \exp[-c_1/(8.314P)]\}$	
12	$\{a \exp[-a_1/(8.314P)]\}\ \exp(-\{k \exp[-k_1/(8.314P)]\}t)+[c+c_1 \ln(P)]$	
13	$\{a \exp[-a_1/(8.314P)]\}\ \exp\{-[k+k_1 \ln(P)]\ t\}+[c+c_1 \ln(P)]$	
14	$[a+a_1 \ln\ (P)]\ \exp\{-[k+k_1 \ln(P)]\ t\}+[c+c_1 \ln(P)]$	
15	$[a+a_1 \ln\ (P)]\ \exp(-\{k \exp[-k_1/(8.314P)]\}t)+[c+c_1 \ln(P)]$	
16	$[a+a_1 \ln(P)]\ \exp\{-[k+k_1 \ln(P)]\ t\}+c \exp[-c_1/(8.314P)]\}$	
17	$[a+a_1 \ln\ (P)]\ \exp(-k \exp[-k_1/(8.314P)]\}t)+\{c \exp[-c_1/(8.314P)]\}$	
18	$\{a \exp[-a_1/(8.314P)]\}\exp\{-[k+k_1 \ln(P)]\ t\}+\{c \exp[-c_1/(8.314P)]\}$	
Wang and Singh: $MR = 1+at+bt^2$		
19	$1+\{a \exp[-a_1/(8.314P)]\}\ t+\{b \exp[-\mathrm{b}_1/(8.314P)]\}t^2$	
20	$1+\{a\exp[-a_1/(8.314P)]\}\ t+[b+b_1 \ln(P)]\ t^2$	
21	$1+[a+a_1 \ln(P)]\ t+\{b \exp[-b_1/(8.314P)]\}\ t^2$	
22	$1+[a+a_1 \ln(P)]\ t+[b+b_1 \ln(P)]\ t^2$	
Diffusion: $MR = a \exp(-kt)+(1-a) \exp(-kbt)$		
23	$\{a \exp[-a_1/(8.314\mathrm{P})]\}\ \exp(-\{k \exp[-k_1/(8.314P)]\}\ t)+(1-\{a \exp[-a_1/(8.314P)]\})$ $\exp(-\{k \exp[-k_1/(8.314P)]\}\ \{b \exp[-b_1/(8.314P)]\}\ t)$	
24	$\{a\exp[-a_1/(8.314P)]\}\exp(-\{k \exp[-k_1/(8.314P)]\}t)+(1-\{a\exp[-a_1/(8.314P)]\})$ $\exp(-k\exp[-k_1/(8.314P)]\}\ [b+b_1 \ln(P)]\ t)$	
25	$\{a \exp[-a_1/(8.314P)]\}\ \exp\{-[k+k_1 \ln(P)]\ t\}+(1-\{a \exp[-a_1/(8.314P)]\})$ $\exp(-[k+k_1 \ln(P)]\ \{b \exp[-b_1/(8.314P)]\}\ t)$	
26	$[a+a_1 \ln(P)]\ \exp(-\{k \exp[-k_1/(8.314P)]\}t)+\{1-[a+a_1 \ln(P)]\}$ $\exp(-\{k \exp[k_1/(8.314P)]\}\ \{b \exp[-b_1/(8.314P)]\}\ t)$	
27	$\{a \exp[-a_1/(8.314P)]\}\ \exp\{-[k+k_1 \ln(P)]\ t\}+(1-\{a \exp[-a_1/(8.314P)]\})$ $\exp\{-[k+k_1 \ln(P)]\ [b+b_1 \ln(P)]\ t\}$	
28	$[a+a_1 \ln(P)]\ \exp\{-[k+k_1 \ln(P)]\ t\}+\{1-[a+a_1 \ln(P)]\}$ $\exp\{-[k+k_1 \ln(P)]\ [b+b_1 \ln(P)]\ t\}$	
29	$[a+a_1 \ln(P)]\ \exp\{-[k+k_1 \ln(P)]\ t\}+\{1-[a+a_1 \ln(P)]\}\ \exp(-[k+k_1 \ln(P)]$ $\{b \exp[-b_1/(8.314P)]\}\ t)$	
30	$[a+a_1 \ln(P)]\ \exp(-\{k \exp[-k_1/(8.314P)]\}\ t)+\{1-[a+a_1 \ln(P)]\}$ $\exp(-\{k \exp[-k_1/(8.314P)]\}\ [b+b_1 \ln(P)]\ t)$	
Verma: $MR = a \exp(-kt)+(1-a) \exp(-gt)$		
31	$\{a \exp[-a_1/(8.314P)]\}\ \exp(-k\{k \exp[-k_1/(8.314P)]\}\ t)+$ $(1-\{a \exp[-a_1/(8.314P)]\})\ \exp(-\{g \exp[-g_1/(8.314P)]\}\ t)$	

(*Continued*)

TABLE 3
Continued

Model no.	Arrhenius Logarithmic	$\{a\ \exp[-b/(8.314P)]\}$ $(\mathrm{a+b\ ln[P]})$
32	$\{-[a+a_1\ \ln(P)]\ \exp(-\{k\ \exp[-k_1/(8.314P)]\}\ t)+(1-\{-[a+a_1\ \ln(P)]\}$ $\exp(-g\ \exp[-g_1/(8.314P)]\}\ t)\}$	
33	$\{a\ \exp[-a_1/(8.314P)]\}\ \exp\{-[k+k_1\ \ln(P)]\ t\}+(1-\{a\ \exp[-a_1/(8.314P)]\})$ $\exp(-\{g\ \exp[-g_1/(8.314P)]\}\ t)$	
34	$\{-[a+a_1\ \ln\ (P)]\ \exp\{-[k+k_1\ \ln(P)]\ t\}+(1-\{-[a+a_1\ \ln(P)]\}$ $\exp(-\{g\ \exp[-g_1/(8.314P)]\}\ t)\}$	
35	$(-[a+a_1\ \ln(P)]\ \exp(-\{k\ \exp[-k_1/(8.314P)]\}\ t)+(1-\{-[a+a_1\ \ln(P)]\}$ $\exp\{-g[-(g+g_1\ \ln(P)]\ t\})$	
36	$\{a\ \exp[-a_1/(8.314P)]\}\ \exp\{-[k+k_1\ \ln(P)]\ t\}+(1-\{a\ \exp[-a_1/(8.314P)]\})$ $\exp\{-[g+g_1\ \ln(P)]\ t\}$	
37	$\{a\ \exp[-a_1/(8.314P)]\}\ \exp(-k\ \exp[-k_1/(8.314P)]\}\ t)$ $+(1-\{a\ \exp[-a_1/(8.314P)]\})\ \exp\{-[g+g_1\ \ln(P)]\ t\}$	
38	$\{-[a+a_1\ \ln(P)]\ \exp(-[k+k_1\ \ln(P)]\ t\}+(1-\{-[a+a_1\ \ln(P)]\}$ $\exp\{-[g+g_1\ \ln(P)]\ t\})$	
Two-term exponential: $MR=a\ \exp(-kt)+(1-a)\ \exp(-kat)$		
39	$\{a\ \exp[-a_1/(8.314P)]\}\ \exp(-\{k\ \exp[-k_1/(8.314P)]\}\ t)+$ $(1-\{a\ \exp[-a_1/(8.314P)]\})\ \exp(-\{k\ \exp[-k_1/(8.314P)]\}$ $\{a\ \exp[-a_1/(8.314P)]\}\ t)$	
40	$\{a\ \exp[-a_1/(8.314P)]\}\ \exp(-\{[k+k_1\ \ln(P)]t\}+(1-\{a\ \exp[-a_1/(8.314P)]\})$ $\exp\{-[k+k_1\ \ln(P)]\}\ \{a\ \exp[-a_1/(8.314P)]\}\ t)$	
41	$\{[a+a_1\ \ln(P)]\}\ \exp(-\{k\ \exp[-k_1/(8.314P)]\}\ t)+$ $(1-\{[a+a_1\ \ln(P)]\}\ \exp(-\{k\ \exp[-k_1/(8.314P)]\}\ [a+a_1\ \ln(P)]\}\ t)$	
42	$([a+a_1\ \ln(P)]\ \exp(-\{[k+k_1\ \ln(P)]\ t\}+(1-\{[a+a_1\ \ln(P)]\}$ $\exp\{-[k+k_1\ \ln(P)]\}\ [a+a_1\ \ln(P)]\}\ t)\}$	
Midilli: $MR=\{a\ \exp[-k(t^n)]+bt\}$		
43	$(\{a\ \exp[-a_1/(8.314P)]\}\ \exp(-\{k\ \exp[-k_1/(8.314P)]\}$ $[t^{\{n\ \exp[-n_1/(8.314P)]\}}])+\{b\ \exp[-b_1/(8.314P)]\}\ t)$	
44	$(\{a\ \exp[-a_1/(8.314P)]\}\ \exp(-\{k\ \exp[-k_1/(8.314P)]\}$ $[t^{\{n\ \exp[-n_1/(8.314P)]\}}])+[b+b_1\ \ln(P)]\ t)$	
45	$\{(a\ \exp[-a_1/(8.314P)]\}\ \exp(-\{k\ \exp[-k_1/(8.314P)]\}$ $(t^{[n+n_1\ \ln(P)]})+[b+b_1\ \ln(P)]\ t)$	
46	$\{(a\ \exp[-a_1/(8.314P)]\}\ \exp\{-[k+k_1\ \ln(P)]\ t^{[n+n_1\ \ln(P)]}\}+[b+b_1\ \ln(P)]\ t)$	
47	$([a+a_1\ \ln(P)]\ \exp(-[k+k_1\ \ln\ (P)]\ (t^{[n+n_1\ \ln(P)]})+[b+b_1\ \ln(P)]\ t)$	
48	$([a+a_1\ \ln(P)]\ \exp(-[k+k_1\ \ln(P)]\ (t^{[n+n_1\ \ln(P)]})+\{b\ \exp[-b_1/(8.314P)]\}\ t)$	
49	$([a+a_1\ \ln(P)]\ \exp\{-[k+k_1\ \ln(P)]\ (t^{\{n\ \exp[-n_1/(8.314P)]\}})\}+$ $\{b\ \exp[-b_1/(8.314P)]\}\ t)$	
50	$([a+a_1\ \ln(P)]\ \exp(-\{k\ \exp[-k_1/(8.314P)]\}\ [t^{\{n\ \exp[-n_1/(8.314P)]\}}])+$ $\{b\ \exp[-b_1/(8.314P)]\}\ t)$	
51	$(a\ \exp[-a_1/(8.314P)]\}\ \exp(-\{k\ \exp[-k_1/(8.314P)]\}\ (t^{[n+n_1\ \ln(P)]})+$ $\{b\ \exp[-b_1/(8.314P)]\}\ t)$	
52	$(\{a\ \exp[-a_1/(8.314P)]\}\ \exp(-[k+k_1\ \ln(P)]\ [t^{n\ \exp[-n_1/(8.314P)]\}}])+$ $\{b\ \exp[-b_1/(8.314P)]\}\ t)$	
53	$(\{a\ \exp[-a_1/(8.314P)]\}\ \exp(-[k+k_1\ \ln(P)]\ (t^{[n+n_1\ \ln(P)]})+\{b\ \exp[-b_1/(8.314P)]\}\ t)$	
54	$([a+a_1\ \ln(P)]\ \exp(-\{k\ \exp[-k_1/(8.314P)]\}\ (t^{[n+n_1\ \ln(P)]})+\{b\ \exp[-b_1/(8.314P)]\}\ t)$	
55	$\{[a+a_1\ \ln(P)]\ \exp(-\{k\ \exp[-k_1/(8.314P)]\}\ [t^{\{n\ \exp[-n_1/(8.314P)]\}}])+[b+b_1\ \ln(P)]\ t\}$	
56	$([a+a_1\ \ln\ (P)]\ \exp\{-[k+k_1\ \ln(P)]\ [t^{\{n\ \exp[-n_1/(8.314P)]\}}]\}+[b+b_1\ \ln(P)]\ t)$	
57	$(\{a\ \exp[-a_1/(8.314P)]\}\ \exp\{-[k+k_1\ \ln(P)]\ [t^{\{n\ \exp[-n_1/(8.314P)]\}}]\}+[b+b_1\ \ln(P)]\ t)$	
58	$([a+a_1\ \ln(P)]\ \exp\{-[k+k_1\ \ln(P)]\ [t^{\{n\ \exp[-n_1/(8.314P)]\}}]\}+[b+b_1\ \ln(P)]\ t)$	

for the selection of the best equation to account for variation in the drying curves.[15,39,46] The residual sum of squares value is an important parameter in the nonlinear regression process, with the fitting procedure being designed to achieve the minimum RSS.[10,49]

RESULT OF DISCUSSION

Effect of Power, Initial Moisture Content, and Shape of Samples

The microwave power supplied to the system plays a major role in arriving at the desired final moisture content, which explains the drying nature of samples. As can be seen in Fig. 2, at high power (540 watts) input levels, the continuous supply of microwave energy produces the sample temperature to attain a point at which the samples begin to crack, while lower power favors maximum drying of POP. Since the solvent used in the sample was water, which is dipolar in nature, the water molecules absorb the microwaves instantly and rapidly. A fast rate and complete drying of POP were accomplished for samples with maximum initial moisture content, whereas comparatively slower rates were observed for cases where the initial moisture content was less, due to the fact that the liquid may flow from the sample because of rapid rate of vapor generation, which causes a pressure gradient within the sample. This period was designated as the liquid movement period and was observed only in samples with higher moisture contents.[50] Further, at maximum moisture content, the sample responded quantitatively large to microwaves, which resulted in immediate and complete drying of POP, whereas samples dried slower when the initial moisture content was reduced. Drying rate decreased continuously with time and decreasing moisture content. During all the experiments (irrespective of shape and power), it was further observed (Fig. 3) that the drying rate was higher for samples with higher initial moisture content, which is impossible to achieve by other conventional drying methods.

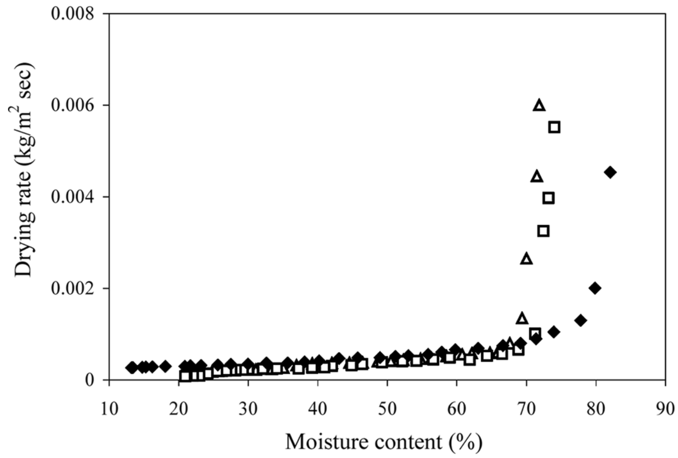


FIG. 3. Drying rate versus moisture content of POP at different initial moisture contents (□: initial moisture content 75%, △: initial moisture content 70%, ◆: initial moisture content 80%). Conditions: rectangle, power 180 W.

Maximum thicknesses of 18, 15, and 13 mm were maintained for cylinder-, square-, and rectangle-shaped samples, respectively. Though the curves obtained for rectangular samples deviated little from those of square and cylindrical geometries, much change was not observed with respect to the geometry of samples (Fig. 4). The range of moisture removal was from 66.40 to 28.55% for rectangular samples

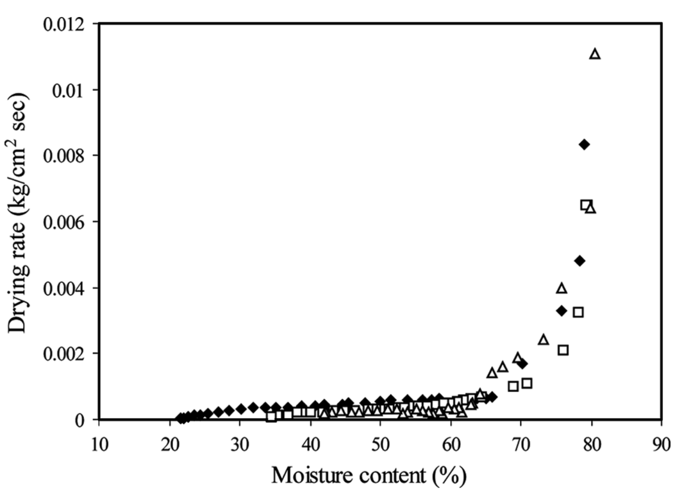


FIG. 2. Drying rate versus moisture content of POP at different power ranges (◆: P, 180 W, □: P, 360 W, △: P, 540 W). Conditions: initial moisture content, 70%; geometry, cylinder.

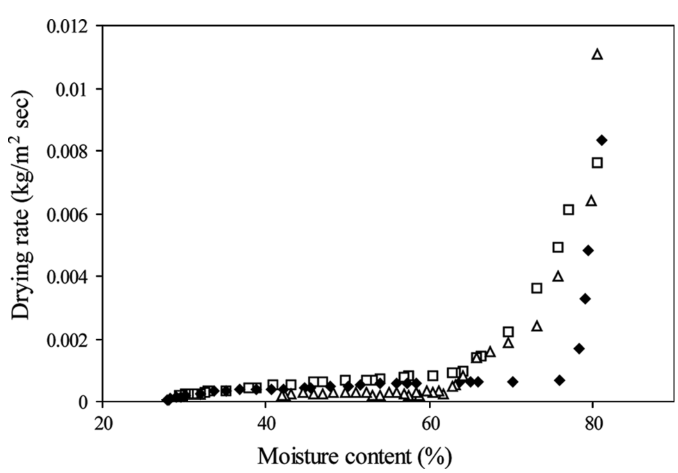


FIG. 4. Drying rate versus moisture content of POP at varied geometries. (□: square, △: cylinder, ◆: rectangle). Conditions: initial moisture content 70%; power, 360 W.

and was from 70.07 to 33.06% and 68.99 to 39.10% for square and cylindrical geometries, respectively. As shown in Fig. 4, it was observed that the drying rate was high at initial periods when compared to other geometries, due to the larger surface area for rectangular geometries; furthermore, the drying rates were identical with other geometries. Based on the above results it was clear that maximum drying rate could be achieved for rectangular samples with a power input of 180 watts and an initial moisture content of 80%. As indicated in this rate of drying curves, there are no constant and falling rate periods during the drying of POP. This shows that diffusion is the dominant physical mechanism governing moisture movement in the sample. These results are in agreement with earlier observations.[12,51]

Characterization

The internal heat generation influences heat and mass transfer effects on samples with a wide change in external as well as internal characteristics of POP, which leads to the estimation of few physical properties including porosity, bulk density, linear shrinkage (square, rectangle), radial shrinkage (cylinder), and volumetric shrinkage for wet and dried samples. The details of the basic characteristics of the sample before and after microwave drying are given in Table 4. The porosity of POP increased after exposure to microwave atmosphere. An average increase of 5% in porosity was noted for all samples, irrespective of geometry, initial moisture content, and power. The porosity of fresh tempered samples varied from 41.20 to 71.0%, where the dried samples were in a range of 43.0

TABLE 4
Characteristics of POP sample before and after microwave drying

		Moisture content (%)		Porosity (%)		Bulk density (gm/cc)	
Sl. no.	Power (watt)	Initial	Final	Initial	Final	Initial	Final
Square ($70 \times 70 \times 15$, $L \times B \times H$ in mm)							
1	180	69.16	27.92	58.41	61.15	1.49	1.04
2	360	70.04	33.06	63.12	66.56	1.19	0.94
3	540	69.92	43.06	62.19	65.00	1.64	0.92
4	180	75.42	25.16	71.00	76.21	1.92	1.23
5	360	74.63	31.43	41.31	43.00	1.33	0.91
6	540	75.41	38.73	53.12	56.62	1.33	0.90
7	180	80.90	17.22	57.76	65.72	2.11	1.14
8	360	80.42	28.62	58.74	62.52	1.20	0.94
9	540	80.15	29.36	60.21	63.06	1.82	1.12
Rectangle ($80 \times 70 \times 13$, $L \times B \times H$ in mm)							
10	180	70.06	22.16	60.06	62.23	1.29	0.79
11	360	70.15	28.55	51.02	56.16	1.20	0.96
12	540	70.63	39.93	56.93	61.19	1.54	0.77
13	180	74.11	20.97	56.31	63.22	1.49	1.04
14	360	75.00	27.41	52.14	61.36	1.51	0.87
15	540	74.42	32.93	41.20	49.35	0.99	0.83
16	180	80.17	13.23	52.12	61.71	1.12	0.88
17	360	79.43	23.00	57.47	61.06	1.80	0.97
18	540	81.83	27.86	61.42	69.43	1.02	0.82
Cylinder (64×18, $D \times H$ in mm)							
19	180	69.26	32.40	42.49	49.06	1.05	0.79
20	360	79.49	39.13	54.04	59.19	1.15	0.85
21	540	70.17	52.17	51.18	56.13	2.00	1.57
22	180	75.25	26.77	59.30	62.06	1.09	0.84
23	360	74.92	37.62	62.03	68.14	2.02	1.68
24	540	75.07	44.73	41.63	45.02	1.05	0.97
25	180	79.17	21.68	48.02	55.00	1.16	0.84
26	360	79.47	34.52	46.41	50.47	1.05	0.99
27	540	80.52	41.94	42.06	45.15	1.42	0.89

TABLE 5
Results of statistical analyses on the modeling of moisture content and drying time

Model name	Constants	R^2
Newton	$k = 0.0023$	0.99843
Page	$k = 0.0060$, $n = 0.8258$	0.99845
Henderson	$a = 0.9694$, $k = 0.0022$	0.99750
Logarithmic	$a = 0.6376$, $k = 0.0056$, $c = 0.3990$	0.99264
Wang and Singh	$a = -0.0025$, $b = 0.000003$	0.99587
Diffusion	$a = 1.0000$, $k = 0.0023$, $b = 1.0000$	0.99831
Verma	$a = 0.9694$, $k = 0.0022$, $g = 1.0000$	0.99750
Two-term exponential	$a = 0.9944$, $k = 0.0023$	0.99831
Midilli	$a = 3.3357$, $k = 0.9366$, $n = 0.0884$, $b = -0.0006$	0.99999

to 76.0%. Shrinkage of material normally occurs in solar drying due to prolonged exposure to sunlight; however, negligible linear, radial, and volumetric shrinkage was found when POP was dried with microwave, irrespective of sample geometry (Table 4). Bulk density, an important physical property in characterizing the texture and the quality of materials, is essential in modeling and design of various heat and mass transfer process. The bulk density decreased in dried samples when compared to the moist ones. The bulk density of POP reduced from a minimum of 0.997 to 0.830 (g cm^{-3}) and from a maximum of 2.110 to 1.138 (g cm^{-3}). No significant change in color was observed between the moist and dried samples. The dried samples were much brighter than the moist samples.

Mathematical Modeling of Microwave Drying Curves

The moisture content data obtained for the three different microwave power supplies, initial moisture contents, and geometries were converted to the most useful moisture ratio expressions. The curve-fitting computations with the drying time were carried out based on the nine basic drying models suggested by the previous workers and the details of the results along with the statistical analyses are given in Table 5 and the efficiency of the basis are shown in Fig. 5. The results of previous investigators have shown that the highest values of r and EF and the lowest values of MBE and RMSE were obtained by using a linear and a power equation for apricots.[52] The dependence of the drying rate constant k on the operating variables is modeled as an Arrhenius-type equation and power model for onion slices as discussed and reported by Rapusas and Driscoll.[53] Validation of the logarithmic models established for describing drying behavior of brined onion slices[46] was made by comparing the computed moisture contents with the all the present drying experimental results.

Even though the literature models were developed exclusively for food materials (apricot, apples, butter fruit, figs, grapes, onions, peaches, plums, etc.), the applicability of those models was analyzed and extended for establishing the drying characteristics of POP. The results have shown that the highest values of EF and the lowest values of chi-square and RMSE could be obtained from using Midilli et al.'s[44] equation when compared with the values of the other models. Therefore, Midilli et al.'s[44] equation can be extended to evaluate the moisture ratio of POP for interval of drying power and time in this study. It should be emphasized that the constants in the table are applicable only to the range of microwave drying power, initial moisture content, and basic geometries in this study. The other models except that of Midilli et al.[44] do not account for the effect of drying variables on POP, which leads to further modification of the basic models to the present system by expressing the constants and coefficients in terms of microwave power and drying rate through Arrhenius and logarithmic type expressions. Hence, the constants or coefficients of the literature models were derived using different combination of Arrhenius and logarithmic functions and, based on that, m^n (=58) new models were derived. The values of these constants and the results of the statistical test are given in Table 6.

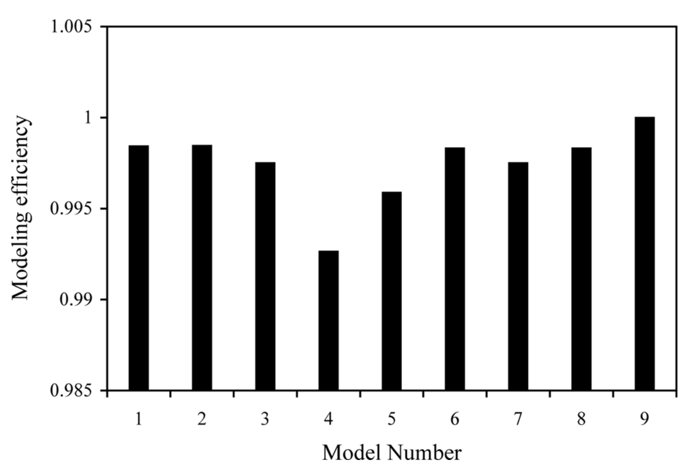


FIG. 5. Modeling efficiency of all basic models in Table 2.

TABLE 6
Values of parameters of derived models and statistical test results

Model 01	Model 02	Model 03	Model 04	Model 05
$a = 0.0023$	$a = 0.0024$	$a = -0.6306$	$a = -0.6298$	$a = -0.7548$
$a_1 = 1.0012$	$a_1 = 1.0251$	$a_1 = 2.9739$	$a_1 = 1.0016$	$a_1 = 2.7315$
RSS = 0.0043	RSS = 0.0045	$n = -0.2113$	$n = 0.7711$	$n = -0.2170$
RMSE = 0.0069	RMSE = 0.0067	$n_1 = 1.5132$	$n_1 = -0.1891$	$n_1 = 1.0005$
$\chi^2 = 0.0071$	$\chi^2 = 0.0068$	RSS = 0.0082	RSS = 0.0011	RSS = 0.0057
EF = 0.967793	EF = 0.969230	RMSE = 0.0904	RMSE = 0.0904	RMSE = 0.0756
		$\chi^2 = 0.0086$	$\chi^2 = 0.0086$	$\chi^2 = 0.0081$
		EF = 0.985631	EF = 0.984247	EF = 0.997280

Model 06	Model 07	Model 08	Model 09	Model 10
$a = 1.1274$	$a = 0.9864$	$a = 0.7548$	$a = 0.3990$	$a = 0.4154$
$a_1 = 0.3383$	$a_1 = 1.0000$	$a_1 = 1.2732$	$a_1 = 0.1228$	$a_1 = 1.9641$
$n = 0.7711$	$k = 0.0021$	$k = 0.0051$	$k = 0.0056$	$k = 0.3199$
$n_1 = -0.1891$	$k_1 = 1.0013$	$k_1 = 0.3447$	$k_1 = -0.0056$	$k_1 = 3.9555$
RSS = 0.0011	RSS = 0.0007	RSS = 0.4530	RSS = 0.0162	RSS = 0.4530
RMSE = 0.0904	RMSE = 0.0256	RMSE = 0.6730	RMSE = 0.0783	RMSE = 0.0673
$\chi^2 = 0.0086$	$\chi^2 = 0.0032$	$\chi^2 = 0.0039$	$\chi^2 = 0.0065$	$\chi^2 = 0.0044$
EF = 0.984262	EF = 0.978556	EF = 0.972800	EF = 0.998126	EF = 0.981100

Model 11	Model 12	Model 13	Model 14	Model 15
$a = 0.0024$	$a = -19.2688$	$a = 1.0000$	$a = 3.9555$	$a = 0.7780$
$a_1 = 1.0017$	$a_1 = 0.9700$	$a_1 = 1.0000$	$a_1 = -2.3831$	$a_1 = -0.1541$
$k = -5.6668$	$k = 0.0336$	$k = 1.0000$	$k = 0.9920$	$k = 2.7919$
$k_1 = 1.4800$	$k_1 = 8.5289$	$k_1 = 4.2727$	$k_1 = 1.1262$	$k_1 = 0.9978$
$c = 0.3577$	$c = 1.7070$	$c = 0.8028$	$c = 0.8019$	$c = 0.8114$
$c_1 = 0.9969$	$c_1 = 3.4564$	$c_1 = -0.0229$	$c_1 = -0.0288$	$c_1 = 0.0208$
RSS = 0.0000	RSS = 0.0001	RSS = 0.0000	RSS = 0.0274	RSS = 0.0000
RMSE = 0.0780	RMSE = 0.0783	RMSE = 0.1723	RMSE = 0.1656	RMSE = 0.0874
$\chi^2 = 0.0066$	$\chi^2 = 0.0066$	$\chi^2 = 0.0032$	$\chi^2 = 0.0039$	$\chi^2 = 0.0083$
EF = 0.982971	EF = 0.986381	EF = 0.975314	EF = 0.983439	EF = 0.989824

Model 16	Model 17	Model 18	Model 19	Model 20
$a = 1.6302$	$a = 0.6080$	$a = -0.1541$	$a = -0.0025$	$a = 0.0002$
$a_1 = 4.2727$	$a_1 = -3.2415$	$a_1 = 2.7919$	$a_1 = 1.0539$	$a_1 = 1.0550$
$k = 0.8011$	$k = 0.0399$	$k = 0.9978$	$b = 0.0000$	$b = -0.2108$
$k_1 = -0.0315$	$k_1 = 8.5861$	$k_1 = 0.0007$	$b_1 = 1.0428$	$b_1 = 0.0000$
$c = 0.7926$	$c = 16.6365$	$c = 0.6528$	RSS = 0.0002	RSS = 0.0013
$c_1 = 0.8011$	$c_1 = 0.9596$	$c_1 = 1.0002$	RMSE = 0.0809	RMSE = 0.1137
RSS = 0.0213	RSS = 0.0001	RSS = 0.0003	$\chi^2 = 0.0069$	$\chi^2 = 0.0094$
RMSE = 0.1461	RMSE = 0.0783	RMSE = 0.1656	EF = 0.995729	EF = 0.991512
$\chi^2 = 0.0070$	$\chi^2 = 0.0066$	$\chi^2 = 0.0077$		
EF = 0.989309	EF = 0.996732	EF = 0.973439		

(*Continued*)

TABLE 6
Continued

Model 21	Model 22	Model 23	Model 24	Model 25
$a = -0.0405$	$a = -0.0624$	$a = 0.0713$	$a = -2.3831$	$a = -5.2801$
$a_1 = -0.0004$	$a_1 = -0.0002$	$a_1 = 1.1764$	$a_1 = 0.9920$	$a_1 = 0.9985$
$b = 0.0000$	$b = -0.0624$	$k = 4.3344$	$k = 1.1262$	$k = 1.0015$
$b_1 = 1.2135$	$b_1 = 0.0000$	$k_1 = 1.1567$	$k_1 = -0.0545$	$k_1 = 0.4968$
RSS = 0.0011	RSS = 0.0129	$b = 1.6391$	$b = -0.0003$	$b = 1.4996$
RMSE = 0.0819	RMSE = 0.0906	$b_1 = 0.9337$	$b_1 = 0.0000$	$b_1 = -0.2063$
$\chi^2 = 0.0071$	$\chi^2 = 0.0087$	RSS = 0.6836	RSS = 0.1483	RSS = 0.4530
EF = 0.999545	EF = 0.991993	RMSE = 0.7050	RMSE = 0.3851	RMSE = 0.6730
		$\chi^2 = 0.0054$	$\chi^2 = 0.0047$	$\chi^2 = 0.0044$
		EF = 0.984608	EF = 0.978700	EF = 0.976000

Model 26	Model 27	Model 28	Model 29	Model 30
$a = 0.9992$	$a = 0.7462$	$a = 0.9996$	$a = -0.0545$	$a = 0.9992$
$a_1 = 0.9957$	$a_1 = -2.1614$	$a_1 = 0.9995$	$a_1 = -0.0003$	$a_1 = 0.9957$
$k = -0.1867$	$k = 0.7632$	$k = 0.7462$	$k = 0.0000$	$k = -0.1867$
$k_1 = 1.0008$	$k_1 = -0.3765$	$k_1 = -2.3831$	$k_1 = -2.1614$	$k_1 = 1.0008$
$b = 7.4000$	$b = 0.9253$	$b = 0.9920$	$b = 0.7632$	$b = 7.4000$
$b_1 = 0.9957$	$b_1 = 0.7462$	$b_1 = 1.1262$	$b_1 = -0.3765$	$b_1 = 0.9957$
RSS = 0.6769	RSS = 0.4530	RSS = 0.4160	RSS = 0.4160	RSS = 0.6730
RMSE = 0.8293	RMSE = 0.6730	RMSE = 0.6450	RMSE = 0.6450	RMSE = 0.4160
$\chi^2 = 0.0040$	$\chi^2 = 0.0039$	$\chi^2 = 0.0044$	$\chi^2 = 0.0044$	$\chi^2 = 0.0041$
EF = 0.979120	EF = 0.979010	EF = 0.979320	EF = 0.979180	EF = 0.979090

Model 31	Model 32	Model 33	Model 34	Model 35
a = 0.9907	$a = 0.8132$	$a = 0.0306$	$a = 0.9637$	$a = 0.8132$
$a_1 = 1.0001$	$a_1 = 0.0301$	$a_1 = 1.0000$	$a_1 = -2.3831$	$a_1 = 0.0301$
$k = 0.0021$	$k = 0.0022$	$k = 1.0000$	$k = 0.9920$	$k = 0.0022$
$k_1 = 1.0013$	$k_1 = 1.0015$	$k_1 = 1.0000$	$k_1 = 1.1262$	$k_1 = 1.0011$
$g = 0.9995$	$g = 1.6708$	$g = 0.0022$	$g = 0.0256$	$g = 1.0000$
$g_1 = 1.0000$	$g_1 = 0.9996$	$g_1 = 1.0013$	$g_1 = 0.9435$	$g_1 = 1.0000$
RSS = 0.0245	RSS = 0.0006	RSS = 0.0006	RSS = 0.9848	RSS = 0.0006
RMSE = 0.0855	RMSE = 0.0817	RMSE = 0.0817	RMSE = 0.0898	RMSE = 0.0817
$\chi^2 = 0.0079$	$\chi^2 = 0.0072$	$\chi^2 = 0.0072$	$\chi^2 = 0.0072$	$\chi^2 = 0.0072$
EF = 0.988836	EF = 0.997484	EF = 0.997466	EF = 0.997800	EF = 0.997471

Model 36	Model 37	Model 38	Model 39	Model 40
$a = 0.4006$	$a = 0.9701$	$a = 0.7462$	$a = 0.9949$	$a = 0.7632$
$a_1 = -2.1614$	$a_1 = 1.0001$	$a_1 = -1.5676$	$a_1 = 1.0000$	$a_1 = 0.3765$
$k = 0.7632$	$k = 0.0022$	$k = -2.3831$	$k = 0.0023$	$k = 0.4006$
$k_1 = -0.3765$	$k_1 = 1.0013$	$k_1 = 0.9920$	$k_1 = 1.0012$	$k_1 = 1.1614$
$g = -5.2801$	$g = 1.0000$	$g = 1.1262$	RSS = 0.0043	RSS = 0.0045
$g_1 = 0.9985$	$g_1 = 1.0000$	$g_1 = -1.5676$	RMSE = 0.0827	RMSE = 0.0673
RSS = 0.4530	RSS = 0.0006	RSS = 0.4530	$\chi^2 = 0.0072$	$\chi^2 = 0.0068$
RMSE = 0.0821	RMSE = 0.0817	RMSE = 0.0898	EF = 0.998306	EF = 0.974000
$\chi^2 = 0.0076$	$\chi^2 = 0.0072$	$\chi^2 = 0.0070$		
EF = 0.989800	EF = 0.997466	EF = 0.978000		

(*Continued*)

TABLE 6
Continued

Model 41	Model 42	Model 43	Model 44	Model 45
$a = 1.0259$	$a = 0.9435$	$a = 6.7452$	$a = 1.0683$	$a = 8.0684$
$a_1 = 1.1343$	$a_1 = -1.5676$	$a_1 = -5.3190$	$a_1 = 0.9301$	$a_1 = -0.1695$
$k = -0.6000$	$k = 0.0256$	$k = 0.9991$	$k = 1.0000$	$k = 1.0016$
$k_1 = 1.0011$	$k_1 = 0.4850$	$k_1 = 1.0009$	$k_1 = 1.0000$	$k_1 = 0.9991$
RSS = 0.0004	RSS = 0.0045	$n = -2.0748$	$n = 1.0001$	$n = 0.6636$
RMSE = 0.0721	RMSE = 0.0673	$n_1 = 2.7662$	$n_1 = 0.9999$	$n_1 = -0.7460$
$\chi^2 = 0.0070$	$\chi^2 = 0.0067$	$b = -0.1956$	$b = 0.9194$	$b = 143.9941$
EF = 0.994500	EF = 0.981100	$b_1 = -2.3449$	$b_1 = -0.0003$	$b_1 = -0.0411$
		RSS = 0.0001	RSS = 0.0000	RSS = 0.0000
		RMSE = 0.0874	RMSE = 0.0874	RMSE = 0.0874
		$\chi^2 = 0.0085$	$\chi^2 = 0.0087$	$\chi^2 = 0.0085$
		EF = 0.999714	EF = 0.998941	EF = 0.999578

Model 46	Model 47	Model 48	Model 49	Model 50
$a = 0.7577$	$a = 1.0011$	$a = 0.9912$	$a = 0.9912$	$a = 0.5781$
$a_1 = 0.7897$	$a_1 = 1.0037$	$a_1 = 0.9544$	$a_1 = 0.8670$	$a_1 = 0.1511$
$k = 0.7897$	$k = 0.9259$	$k = 1.0556$	$k = 0.8826$	$k = 0.9999$
$k_1 = -1.8838$	$k_1 = 0.4897$	$k_1 = 1.2889$	$k_1 = 0.1743$	$k_1 = 1.0001$
$n = 0.7908$	$n = 0.0380$	$n = 0.5358$	$n = -0.1304$	$n = -6.7732$
$n_1 = -0.1659$	$n_1 = -3.9958$	$n_1 = -1.4108$	$n_1 = 1.9632$	$n_1 = -3.1806$
$b = -0.2776$	$b = 4.7513$	$b = 0.9530$	$b = -0.0537$	$b = -24.1273$
$b_1 = -0.0001$	$b_1 = -0.0014$	$b_1 = 1.0008$	$b_1 = -3.6370$	$b_1 = 3.1272$
RSS = 0.0001	RSS = 0.0000	RSS = 0.2610	RSS = 0.0004	RSS = 0.0000
RMSE = 0.0777	RMSE = 0.0874	RMSE = 0.4976	RMSE = 0.0874	RMSE = 0.0778
$\chi^2 = 0.0067$	$\chi^2 = 0.0085$	$\chi^2 = 0.0027$	$\chi^2 = 0.0085$	$\chi^2 = 0.0067$
EF = 0.999966	EF = 0.994234	EF = 0.980355	EF = 0.999818	EF = 0.999900

Model 51	Model 52	Model 53	Model 54	Model 55
$a = 0.8541$	$a = 1.5950$	$a = 0.6619$	$a = 0.8283$	$a = 0.8114$
$a_1 = -719.0096$	$a_1 = 0.5379$	$a_1 = 0.9455$	$a_1 = 0.1029$	$a_1 = 0.0207$
$k = -263.7573$	$k = 0.5379$	$k = 0.9455$	$k = 1.0007$	$k = 1.0002$
$k_1 = 265.6430$	$k_1 = -1.5088$	$k_1 = -1.9111$	$k_1 = 0.9993$	$k_1 = 0.9998$
$n = -84.9052$	$n = 0.7375$	$n = 1.0501$	$n = 0.2242$	$n = 0.9997$
$n_1 = -16.3284$	$n_1 = 1.2612$	$n_1 = -0.2232$	$n_1 = 0.0641$	$n_1 = 1.0003$
$b = -0.0181$	$b = -3.4492$	$b = -0.0046$	$b = -1.3824$	$b = 0.7811$
$b_1 = -4.0435$	$b_1 = 0.5249$	$b_1 = -5.4365$	$b_1 = 0.2676$	$b_1 = -0.1507$
RSS = 0.0001	RSS = 0.0000	RSS = 0.0000	RSS = 0.0000	RSS = 0.0000
RMSE = 0.0778	RMSE = 0.0874	RMSE = 0.0778	RMSE = 0.0778	RMSE = 0.0874
$\chi^2 = 0.0067$	$\chi^2 = 0.0024$	$\chi^2 = 0.0067$	$\chi^2 = 0.0067$	$\chi^2 = 0.0020$
EF = 0.999326	EF = 0.999997	EF = 0.999879	EF = 0.999876	EF = 0.999999

(*Continued*)

TABLE 6
Continued

Model 56	Model 57	Model 58
$a = 1.3192$	$a = 1.0000$	$a = 0.9998$
$a_1 = 2.6501$	$a_1 = 1.0000$	$a_1 = 0.9990$
$k = 0.9164$	$k = 1.0000$	$k = 1.0012$
$k_1 = 0.2746$	$k_1 = 1.0000$	$k_1 = 1.0063$
$n = -0.0974$	$n = 1.0000$	$n = 1.0000$
$n_1 = 1.0040$	$n_1 = 1.0000$	$n_1 = 1.0000$
$b = -0.0689$	$b = 0.9197$	$b = 0.9074$
$b_1 = -0.0001$	$b_1 = -0.0003$	$b_1 = -0.0003$
RSS = 0.0002	RSS = 0.0000	RSS = 0.0000
RMSE = 0.0777	RMSE = 0.0874	RMSE = 0.0874
$\chi^2 = 0.0067$	$\chi^2 = 0.0085$	$\chi^2 = 0.0085$
EF = 0.999906	EF = 0.998194	EF = 0.998189

Modeling efficiency of 58 models having values greater than 0.93 and chi-square values are given in Figs. 6 and 7, respectively.

Although modeling efficiency of all models in Table 5 are sufficient for modeling of drying curves of microwave-dried plaster of Paris, only 22 models satisfactorily responded to the current system. Model 4 derived from Page's equation; model 9 from Henderson's approach; model 17 from modified logarithmic form; models 19–22 derived from Wang and Singh; models 32–35 and 37 from Verma's approach; models 39 and 41 from a two-term approach; and models 49–52 and 54–58 from Midilli's equation have better values of modeling efficiency than the other models.

When we examined the effect of drying power and moisture content on the constants and coefficients of the model due to Midilli et al.,[44] using multiple regression and the results shown in Fig. 8, RMSE values have varied between 0.07767 and 0.49761 and chi-square between 0.001985 and 0.00866 for different experimental conditions. EF also varied between 0.98035 and 0.99999, indicating the satisfactory agreement of the model with the experimental results. Model 55 gave the highest EF value and lowest chi-square value and were selected to represent

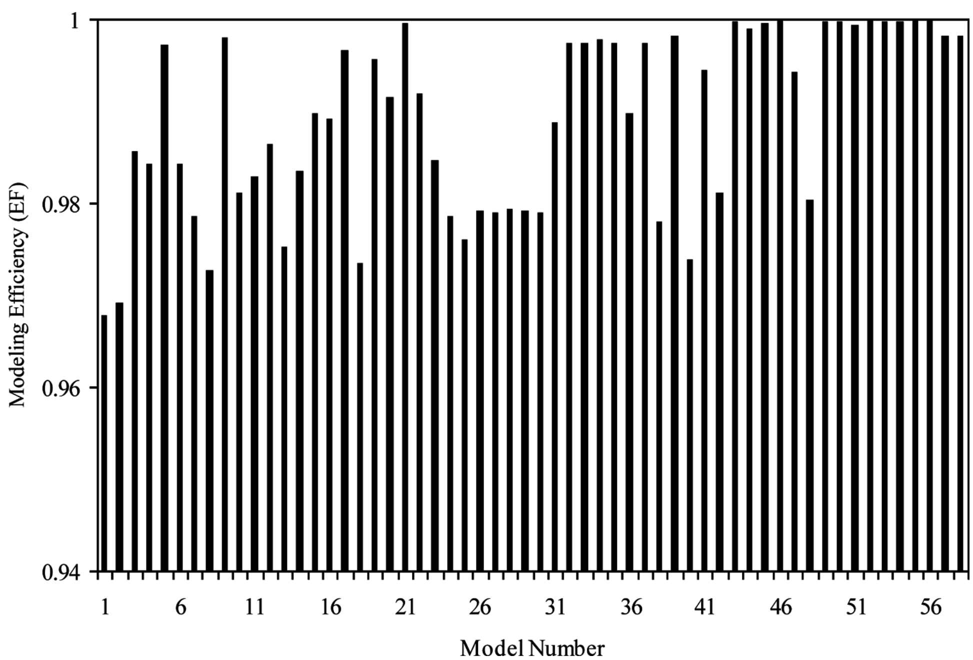


FIG. 6. Modeling efficiency values of model equations of all derived models.

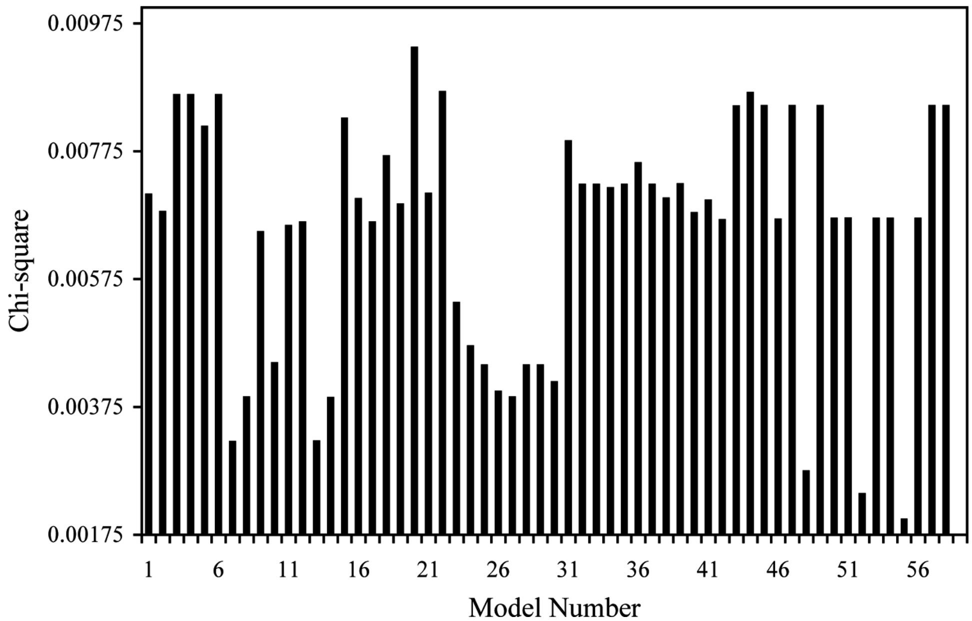


FIG. 7. Chi-square values of model equations of all derived models.

the present data obtained for microwave drying of plaster of Paris. Based on this, the following equation (model 55) is suggested to evaluate the moisture ratio of plaster of Paris as a function of drying time and power supplied to microwave.

$$MR = \left\{ 0.8114 + 0.0207\ln(P) \left\{ \exp - \left[1.0002 \exp \left(\frac{-0.9998}{8.314P} \right) \right] \right\} \left[t^{0.9997 \exp\left(\frac{-1.0003}{8.314P}\right)} \right] + [0.7811 - 0.1507\ln(P)t] \right\} \tag{7}$$

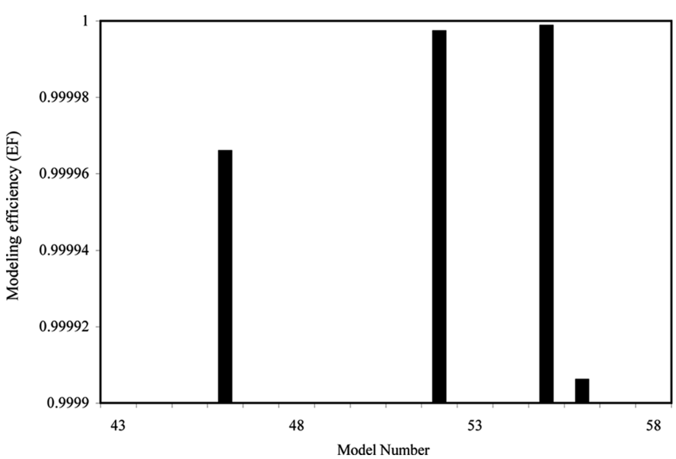


FIG. 8. Modeling efficiency of all derived Midilli's equations.

To validate the applicability of the proposed extended model (Eq. (7)), the experimental and predicted drying data on the moisture ratio were compared. Figure 9 shows a comparison of the experimental and predicted moisture ratio values with drying time for plaster of Paris under microwave drying. Based on the comparison of results it can be concluded that the experimental data could be satisfactorily represented (RMSE = 0.0874; $\chi^2 = 0.0020$; EF = 0.9999) using the present proposed extended empirical model (model 55).

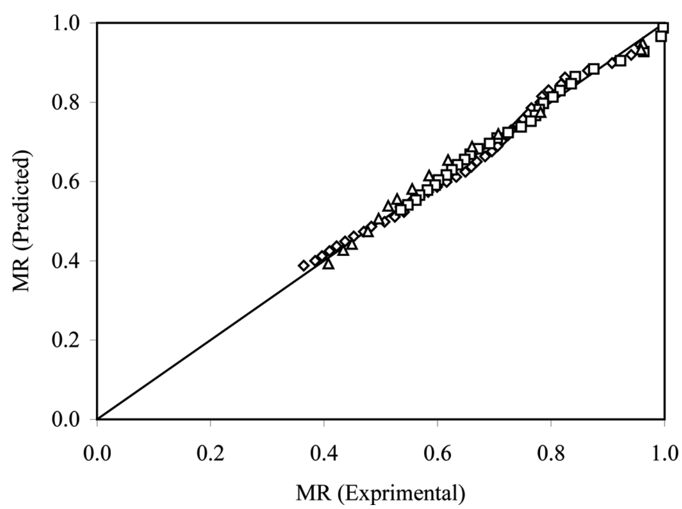


FIG. 9. Predicted and experimental moisture content of POP during microwave drying (□: power 180 W, □: power 360 W, △: power 540 W).

CONCLUSIONS

The drying characteristics of plaster of Paris (POP) were made under microwave conditions using three different power supplies, initial moisture contents, and sample geometries. The measured moisture ratio was analyzed for its dependency on the above-mentioned variables. The suggested models for the microwave drying of food materials were analyzed and the results of the statistical data were reported. An extended empirical model was developed based on Midilli et al.'s equation to represent the present experimental results (Equation 7). This present proposed model should be useful for the design and scale up of the microwave drying process for ceramic industries.

NOMENCLATURE

a, a_0, a_1	Empirical coefficients in models
B	Breadth (mm)
b, b_0, b_1	Empirical coefficients in models
c, c_0, c_1	Empirical coefficients in models
D	Depth of cylinder (mm)
H	Height (mm)
k, k_0, k_1	Empirical coefficients in models
L	Length (mm)
L, L_0, L_1	Empirical coefficients in models
M	Moisture content (kg water/kg dry solids)
Me	Equilibrium moisture content (kg water/kg dry solids)
MR	Moisture ratio
$MR_{\text{exp, avg}}$	Average value of experimental moisture ratio
$MR_{\text{exp}, i}$	ith Experimental moisture ratio
$MR_{\text{pred}, i}$	ith Predicted moisture ratio
M_0	Initial moisture content (kg water/kg dry solids)
m	Number of combination equations
n	Total number of constants and coefficients
n, n_0, n_1	Empirical coefficients in models
P	Microwave power (watts)
r_{avg}	Average regression coefficient
t	Time (s)
W	Width (mm)
X	Moisture content at time t (kg kg^{-1} solid)
X_c	Equilibrium moisture content (kg kg^{-1} solid)
X_0	Initial moisture content (kg kg^{-1} solid)

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