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Optimization of Drying Process for Green Bricks Using Response Surface Methodology

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Drying operation should be under control due to the possible occurring of shrinkage. Shrinkage is an undesired process due to possible causing cracks, deformation, etc. on the product. There are various reasons for shrinkage related to drying process conditions and dried samples. In this study, a laboratory-scale tunnel dryer was operated for examining the influence of drying air temperature and velocity on the drying time of green brick samples with various clay contents (40 % - 60 %). The drying air temperature was varied between 323.15 K - 343.15 K, while the velocity was between 1.0 m/s - 3.0 m/s. The results indicated that the drying time became shorten with increasing the drying air temperature and velocity. The contrariwise effect was observed with increasing the clay content of green brick samples. The effect of these three variables on the drying time of the samples was investigated by applying the central composite design.

Keywords: Central-Composite Design, Drying time, Green Brick, Tunnel Dryer

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Introduction

Brick is an important building material by reason of having unique properties such as strength, durability, fire resistance, beauty, and satisfactory bond and performance with mortar[1,2]. Clay is one of the main ingredients of bricks besides clayey soils, soft slate, and shale[1]. The production process of clay bricks includes preparing of clay soil paste with water, molding, drying, and firing. The drying process can be described as evaporation of the water and is of great influence on the quality of the brick product. Therefore, this process conditions should be under control due to possible occurring shrinkage, which can result in cracks, deformations, and so on. The properties of the brick bodies such as initial moisture content, clay percentage etc. are of also a great contribution to the shrinkage besides especially the drying air properties such as temperature, velocity, etc. In literature, there are lots of studies focused on the effect of various variables on the shrinkage behavior of clay[3,4]. These investigated parameters are also considered to optimize the drying time of bricks, which can lead to minimizing the energy consumption of the process. Kowalski and Pawłowski examined the effect of changing temperature and humidity of the drying medium (air) on the quality of bricks, drying time, and the energy consumption during the drying process in a laboratory chamber. They revealed that non-stationary conditions more suitable than stationary in terms of the quality of the product, while slight differences were observed in drying time[5]. Moropoulou et al. were performed an experimental study and modeled the results for drying of stone materials, bricks, and plasters. They analyzed the influence of drying air properties such as temperature and velocity, and relative humidity on the drying air constant. The results suggested that the drying time decreased with increasing air velocity and decreasing relative humidity[6]. Chemkhi and Zagrouba studied with different drying air temperatures (40 °C - 60 °C) and relative humidities (30 % - 60 %) at a constant drying air velocity of 2 m/s for drying of clay material. They revealed that the ambient temperature and the moisture content, and the physical structure of the product influenced the moisture diffusivity[7].

Even though the influence of various parameters was investigated in the literature, the combined effect of the clay content of brick samples, temperature, and velocity of the drying air on the drying time have not been examined in detail yet. Therefore, this study was focused on the interaction of these parameters in a laboratory-scale tunnel dryer. The green bricks were used as samples in this study. The complicated results of this study were evaluated by response surface methodology (RSM) based on Central-Composite Design (CCD).

Experimental Method and Design

A laboratory-scale tunnel dryer constructed in a previous study[8] was run for the green brick samples with clay contents, 40 % to 60 %, with increasing 5 % per each experiment. These samples were supplied from a brick factory. The samples were dried using different drying air temperatures (from 323.15 K to 323.15 K) with various air velocities (from 1.0 m/s to 3.0 m/s). The experimental study was performed under five different values of each variable represented in Table 1. The tunnel dryer system consists of three main parts; the tunnel dryer unit, the air preparation unit, and the control system. The drying air was prepared by an adjustable centrifugal fan and electrical heater. The drying air temperature was adjusted by a PID-controlled 500-W electric heater (Primus Company Ltd., Thailand). The uniformity of the airflow in the dryer was provided by using a wire meshes system. Before starting each experiment, the steady-state test conditions were checked, and then a green brick sample was placed on the wire mesh carrier. The change in sample weight was determined by the digital balance in every 5 min. The sample surface temperature was measured by a Pt-100 with an accuracy of ±0.1 ºC in every 20 s, which was connected to a computer with a data acquisition device (MCC, USA). All the samples remained in the tunnel dryer until the final moisture content was 0.06 kg H_2O/kg dry brick. The effects of the clay content of brick samples, temperature, and velocity of the drying air on the drying time were measured, and each experiment was repeated three times.

The combined effects of these variables on the drying time of green bricks were examined by CCD in RSM by Design Expert 10 statistical software. CCD is one of the most popular experimental design techniques used to optimize the process parameters. The interaction effect of two variables on the drying time revealed at a constant level of the third variable. The significance of variables with different units might only be compared by coding them. Drying air temperature (K) and velocity (m/s) and clay content of green brick (%) were the independent variables, while the dependent variable was the drying time of green bricks (min). The effect of these independent variables was analyzed at three levels: high (-1), zero (0), and low (-1) levels[9,10]. The range and levels of variables are listed in Table 1. The actual design with the coded and actual levels of variables and experimental results as observed values are illustrated in Table 2. The experimental data were analyzed by fitting to a quadratic model. The significance of this model was determined by performing the Analysis of Variance (ANOVA) and lack-of-fit test.

Results and discussion

Drying experiments

The effects of three variables; clay content of sample, drying air temperature, and velocity on the drying time of a green brick sample, were examined in a laboratory-scale tunnel dryer. The results showed that the drying time highly depends on the drying air temperature. The less influence was observed with changing the drying air velocity and clay content of the sample. The results of drying air velocity effect on the drying time conform to those described by Chemkhi and Zagrouba[7]. The dependency of drying time on these variables can be summarized as the drying time of a green brick sample decreases with increasing the drying air temperature and velocity, while an increase in the green brick clay content results in increasing the drying air time. The experimental results are represented with the actual level of variables and observed drying time on the right-side of Table 2.

Table 1. The range and levels of variables.

Variables	Range and levels				
	-1.68179	-1	0	1	1.68179
A: Drying air temperature (K)	323.15	328.15	333.15	338.15	343.15
B: Drying air velocity (m/s)	1.0	1.5	2.0	2.5	3.0
C: Clay content of green brick (%)	40	45	50	55	60

Central composite design (CCD)

As indicated, the evaluation of three variables' effects is more complicated, and the RSM was used to optimize the conditions. An equation was developed for the drying time to correlate the clay contents of green brick samples, drying air temperature, and velocity variables. The polynomial model equation as a function of variables in coded units obtained for the drying time of green bricks is presented in Equation (1).

$$Y_{drying\ time} = 259.95 - 38.38A - 1.37B + 8.05C - 0.50AB + 1.75AC - 6.06A^2 - 0.054B^2 - 4.65C^2 \quad (1)$$

As can be understood from Equation (1), the increase in positive value; clay content of green brick (C) results in an increase in the drying time of green bricks while it decreases with increasing negative values; drying air temperature (A) and drying air velocity (B). The model was tested statistically by ANOVA technique, and the results are listed in Table 3.

The probability value, p-value determined as < 0.0001, smaller than 0.05 ($p\text{-value} < 0.05$) refers to the model is significant statistically. The correlation coefficient (R^2) value obtained as 0.9865 points out that the model equation fits with the experimental results. The sample variation of more than 98.65 % is attributed to the independent variables, and about 1.35 %

of the total variance cannot be explained by the model. The relationships of the drying time with the interaction effect of two variables; drying air temperature-drying air velocity or drying air temperature-clay content of green brick or drying air velocity-clay content of green brick at a constant level of the third variable are represented in Figure 1.

Each plot seen in Figure 1 presents the influence of two variables on the drying time of green bricks with the third variable fixed to the zero level. The response surface can be evaluated for examining the tendency of each factor affecting the drying time of green bricks. As for the contour plots, the shape of them can be analyzed for the natures and extents of the interactions between factors. While a circular contour plot indicates a negligible effect, an elliptical contour plot points out a prominent interaction[11]. Based on the figures, the drying air temperature and clay content of the green brick sample had a greater effect than the drying air velocity on the drying time.

Table 2. Central composite design consisting of experiments for the study of three experimental factors in coded and actual levels with experimental results.

	Coded level of variables			Actual level of variables			Observed
Test Number	x_1	x_2	x_3	*Drying air temperature (K)*	*Drying air velocity (m/s)*	*Clay content of green brick (%)*	*Drying time (min)*
1	0	0	1.68179	333.15	2	60	265
2	1	1	1	338.15	2.5	55	220
3	1.68179	0	0	343.15	2	50	170
4	0	0	0	333.15	2	50	260
5	0	0	0	333.15	2	50	260
6	-1	-1	1	328.15	1.5	55	290
7	1	-1	-1	338.15	1.5	45	209
8	1	-1	1	338.15	1.5	55	224
9	-1	1	1	328.15	2.5	55	288
10	1	1	-1	338.15	2.5	45	205
11	0	0	0	333.15	2	50	260
12	0	0	0	333.15	2	50	260
13	0	0	0	333.15	2	50	260
14	-1	-1	-1	328.15	1.5	45	282
15	-1.68179	0	0	323.15	2	50	314
16	0	0	-1.68179	333.15	2	40	227
17	-1	1	-1	328.15	2.5	45	280
18	0	-1.68179	0	333.15	1	50	261
19	0	1.68179	0	333.15	3	50	257
20	0	0	0	333.15	2	50	260

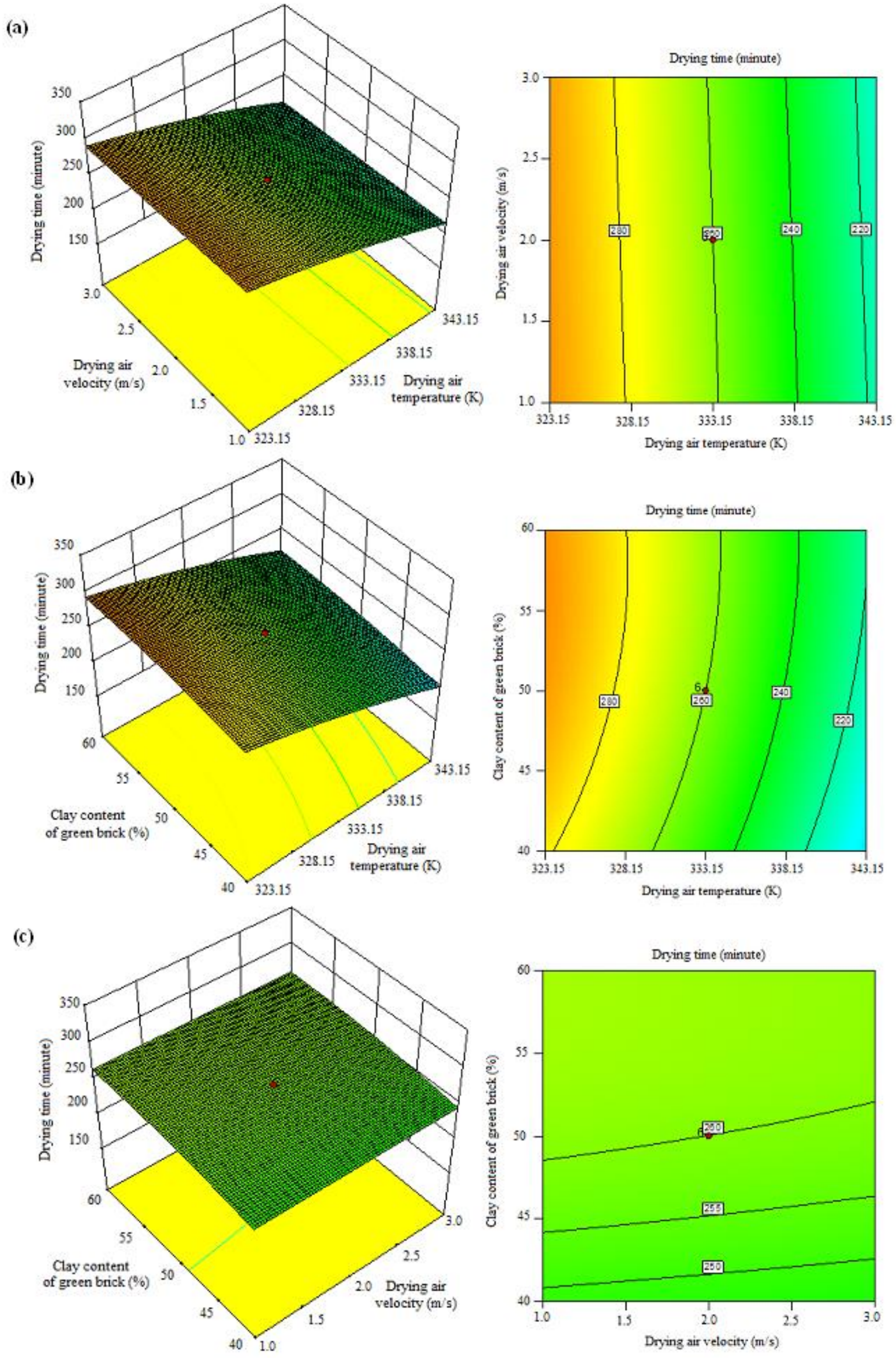

Fig. 1. Response surface and contour plots with respect to the impact of (a) drying air velocity and drying air temperature (b) clay content of green brick and drying air temperature, (c) clay content of green brick and drying air on the drying time of green bricks.

Conclusions

Central composite design (CCD) with RSM was used to elucidate the influence of drying air temperature, drying air velocity, and clay content of green brick on the drying time of green bricks. The second-order polynomial equation was developed to reveal the relationship between the drying time of green bricks and three parameters; drying air temperature, drying air velocity, and clay content of green brick. Following conclusions have been withdrawn from this study:

Table 3. ANOVA results of the quadratic model for drying time of green bricks with different clay content.

ANOVA for Response Surface Quadratic model

Source	Sum of squares	df	Mean square	F-value	p-value	
					Prob > F	
Model	21836.62	9	2426.29	81.37	< 0.0001	significant
A-Drying air temperature	20119.04	1	20119.04	674.74	< 0.0001	
B-Drying air velocity	25.68	1	25.68	0.86	0.3753	
C-Clay content of green brick	884.52	1	884.52	29.66	0.0003	
AB	2.00	1	2.00	0.067	0.8009	
AC	24.50	1	24.50	0.82	0.3860	
BC	0.000	1	0.000	0.000	1.0000	
A^2	530.09	1	530.09	17.78	0.0018	
B^2	0.043	1	0.043	0.001434	0.9705	
C^2	311.70	1	311.70	10.45	0.0090	
Residual	298.18	10	29.82			
Lack of Fit	298.18	5	59.64			
R^2	0.9865					

- The drying time highly depends on drying air temperature while there is a little interaction of drying air velocity and clay content of green brick samples with drying time.
- The proposed model fits the experimental data with a coefficient of determination, R^2 of 0.9865.
- According to all evaluation, the drying time could be under control with drying air temperature.

All experimental results and theoretical evaluations may allow optimizing the drying time and thus energy consumption.

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