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Optimizing production parameters of ceramic tiles incorporating fly ash using response surface methodology

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Abstract

Selection of the process input parameters that would produce a sintered ceramic tile with high flexural strength, low water absorption and shrinkage is the main challenge. Generally, multiple parameters such as temperature, constituent content and type, either independently or interactively affect the efficiency of sintering process. Therefore, response surface methodology (RSM) was used to optimize the responses of these three input variables. Analysis of variance (ANOVA) showed the results of the test of significance of factors and interactions for the responses. The temperature and fly ash (FA) contents are the factors most associated with the output parameters. However, the FA type is the factor that has insignificant effect on responses. RSM demonstrated that predicted values were reasonably close to the experimental values confirming the validity and reliability of the suggested models.

Keywords: A. Sintering; C. Strength; D. Traditional ceramics

1. Introduction

Recently, attempts have been made to use solid wastes in the development of building materials. There are also innumerable environmental reasons why sustained efforts should be made to reduce the amount of solid wastes [1]. Nabozny et al. [2] suggested that processing of by-products (ash, and slag) from power generation by sintering in shaft furnace seemed to be one of the most valuable options for treatment of such residues. The selection of raw materials for fly ash added ceramic tile is of utmost importance as it plays a vital role in ultimate product quality [3]. FA particles are mostly spherical in shape and range from less than 1 μm to 100 μm with a specific surface area, typically between 250 and 600 m^2/kg [4]. Physical properties of FA mainly depend on the type of coal burned and the burning conditions. FA contains valuable oxide resources such as SiO_2, Al_2O_3, CaO, Fe_2O_3, and other oxides [5]. These oxides have been mainly considered as a low cost material resource for the ceramic industry. Moreover, FA is presented as a fine dust so it can be directly incorporated into ceramic pastes, with almost no pre-treatment. It is notable that the alkali and alkaline content, Na_2O, K_2O, and CaO in particular, of FA can vary considerably. Since oxides of the alkali and alkaline metals are known to flux glass, such can greatly alter the sintering behavior of FA [4]. In an investigation [5], properties of different FA types were investigated and different results were obtained due to the difference in their physical and chemical properties. The properties of the produced materials are dependent on the sintering conditions. Moreover, the heating rate is a very important factor to be studied in detail as the manufacture of ceramic process involves rapid sintering conditions of FA porous bodies [6]. In a study [7], the researchers proved that sintering temperature had a more significant effect on characteristics than retention period. Another investigation results showed that the micro-structural changes induced by increasing the sintering temperature [8]. On the other hand, researchers reported that the shapes of pores in general were irregular, spherical, and discrete, while others were elongated and interconnected in

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the structure of sintered FA without binders [9]. Regardless of the type of municipal solid waste FA tested, all the sintered specimens exhibited low strength (4.2–6.3 N/mm^2) [10]. During the sintering process, after heating, particles of municipal solid waste incinerator FA binded to one another giving greater strength [11]. The suitability of FA for the sintering processes is difficult to predict because many physico-chemical factors are involved [12].

In most cases, the sintering kinetics are determined by several parameters including pressed density, material, particle size, sintering atmosphere, temperature and even the degree of sintering [13,14]. The major variables which determine sinterability and the sintered microstructure of a powder compact may be divided into two categories [15]: material variables and process variables. The variables related to raw materials (material variables) include chemical composition of powder compact, powder size, powder shape, powder size distribution, degree of powder agglomeration, etc. These variables influence the powder compressibility and sinterability (densification and grain growth).

To summarize, efficiency of the sintering process is influenced by multiple parameters such as sintering temperature, constituent content and type, among others, and their effects may be either independent or interactive. The influence of sintering variables such as temperature, constituent content and type on the ceramic tile properties has not yet been reported clearly. Therefore, sintering temperature, FA content and type were the three parameters investigated. Using design of experiments based on RSM, the sintered ceramic tile properties having minimum shrinkage and water absorption and maximum flexural strength were arrived with minimum number of experiments without the need for studying all possible combinations experimentally.

2. Experimental data used and procedure details

The experimental data used in this study for optimization work were taken from previous investigations [16,17]. In pronounced investigations, the materials used and experimental procedure applied on specimens for determination of flexural strength, water absorption and shrinkage are as in the following.

The FA samples used were provided from two different locations, namely, Tuncbilek (T) and Seyitomer (S) power plants. These fly ashes were classified according to the ASTM classification [18] as Class F, which accounts for the low content of calcium oxide and the high content of $SiO_2+Al_2O_3+Fe_2O_3$.

The flexural strength of the sintered specimens was evaluated using a three-point flexural strength test on a universal testing machine. The average values of the flexural strength were calculated by the following equation:

$$\sigma_f = 3 \times F \times L/2 \times b \times h^2 \quad (1)$$

where F is the breaking load (kg), L is the span length, b is the tile width (mm) and h is the tile thickness (mm).

The water absorption (%) of the produced materials was determined by the boiling water method using the procedure outlined in the ASTM C 20 [19].

$$W(\%) = \left(W_s - W_d/W_s\right) \times 100 \quad (2)$$

where W_s is the weight of the specimen in saturated surface dry conditions and W_d is the weight of an oven-dried specimen.

The sample shrinkage was determined from the differences in the sintered sample sizes. The % linear shrinkage was evaluated by the formula given below:

$$L(\%) = \left(L_1 - L_2/L_1\right) \times 100 \quad (3)$$

where L_1 and L_2 are the accurately measured length of the green and sintered tile samples, respectively.

The tests mentioned above were performed on three samples from each batch.

3. Optimization of preparation parameters

RSM comprises a group of statistical techniques for model building and model exploitation [20–22]. In these techniques, the main objective is to optimize the response surface that is influenced by various process parameters [23,24]. By careful design and analysis of experiments, it seeks to relate a response or output variable to the levels of a number of predictors or input variables that affect it. Further the input levels of the different variables for a particular level of response can also be determined. RSM has shown to be a powerful tool in optimizing experimental conditions to maximize or minimize various responses.

Historical data design under RSM was used to analyze the interactive effect of temperature, FA content and FA type and to arrive at an optimum. This method helps to optimize the effective parameters with a minimum number of experiments, as well as to analyze the interaction effect between those parameters [22].

The three variables chosen for the study were namely, sintering temperature, FA content and FA type, designated as A, B, C whereas the predicted responses, namely, shrinkage, water absorption and flexural strength, were each designated as Y. Table 1 shows the process variables and output parameters (responses). The mathematical relationships between the variables and the responses were approximated by the second order polynomial.

The factors with their low and high levels were entered to run the software and to obtain the design points by using RSM. However, tiles with 20% Tuncbilek fly ash (TFA) and 20% Seyitomer fly ash (SFA) were not included due to the usefulness of these types of tiles. As previously stated [16], these tile types bloated extremely because of the evolving gas and lost their structure entirely because of the presence of a high level of $CaSO_4$ in the as-received fly ash during sintering at high temperatures. These production difficulties made these tile types undesirable. Temperature and FA content were numeric factors, FA type was a categoric factor.