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# Multi-objective optimization of influential factors on production process of foamed concrete using Box-Behnken approach

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## HIGHLIGHTS

- Box-Behnken design was applied to multi-objective optimization of foamed concrete.
- Empirical models were derived to describe the relationship between factors and responses.
- Maximum strength and minimum cost in the specified density ranges was considered.
- Determining precise mix-designs based on specified density-strength was addressed.
- The manufacturer can reach the best density and strength in line with minimum cost.

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## ABSTRACT

Foamed concrete is a type of lightweight concrete produced from cement, water, foam and sand; however, no sand is required for making low density foamed concrete. Foam is generated from mixing of water and foaming agent under high pressured air. The two most important outputs of foamed concrete production process are dry density and compressive strength in 28 days after the time of mixing which are considered as the physical-mechanical properties. Furthermore, the cost of materials is a very critical issue. The aim of this paper is to optimize the ratio of three effective factors for foamed concrete production including cement mass, water and foam volume in order to achieve minimum density and maximum compressive strength along with minimum cost. To this end, the Box-Behnken design of response surface methodology has been used for optimization purposes. 15 experimental samples were prepared and MINITAB statistical software was employed to analyze and determine the mix-design of materials in different ranges of densities based on their applications. The result reveals that Box-Behnken design leads to optimized values of foamed concrete production outputs. Finally, the optimum values of each input factors for some critical densities and their corresponding compressive strengths were obtained.


## 1. Introduction

In the process of concrete production, most significant input variables are the quantities and ratios of main materials due to their critical roles in the final production features. Once the ratios of materials are optimized, the output variables including mechanical and physical properties as well as cost will improve, which boosts the quality of the finished product. Desirable values of these mechanical and physical properties of concrete depend on the intended place in the building, the structure type, the direction and magnitude of different forces, exerted on it. Although other factors including the type of used materials, curing conditions, facilities together with equipment, environment, and the knowledge as well as the skill of engineers are important, the accurate ratios of main contents should be determined more precisely. Thus, the optimization of main materials and their mix-design has been one of the most challenging tasks for civil engineers. The mix-design of concrete is currently determined based on the producer's experience and speculation. This trial and error approach, is time-consuming and inaccurate which does not rest on scientific fact. In this research, non-autoclaved aerated concrete or foamed concrete, which is one type of lightweight concrete, is chosen as a case study. Foamed concrete is the result of mixing the foam obtained from combining foam agent and water in foam generator with the mixture of cement, water and sand. There is no standard procedure to prepare foamed concrete. Due to the fact that applications of this type of concrete have been increased over the last recent years, improving the methodology of its preparation is an urgent need. Compressive strength is a very critical characteristic of concrete

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and the quality of concrete and its structure are all in direct relationship. The compressive strength could be considered as a representative for all properties of concrete such as permeability, durability and abrasion resistance [1]. An ideal foamed concrete should have high compressive strength and low density and production cost. Box-Behnken Design (BBD), as one of the crucial techniques in Response Surface Method (RSM), and MINITAB software introduce a statistical, systematic and precise method for the optimization and determination of foamed concrete's mix-design. Therefore, in this model, input variables are considered as the content ratio of foamed concrete in volume 1 $m^3$ comprising of cement, water and foam while output variables are considered compressive strength, volumetric density and production (material) cost.

Moreover, DOE-based statistical methods have been implemented to optimize different types of concrete characteristics. For instance, RSM technique and design-expert software were applied to create a relationship between input factors and responses of fly-ash lightweight concrete's production [2]. High strength self-compacting concrete (HSSCC) samples were obtained in a multi-objective approach by the Taguchi method [3]. Taguchi method was applied to optimize mechanical and physical properties of pervious concrete [4]. Furthermore, the properties of Alkali-slag concrete (ASC) under freeze-thaw cycles were optimized using Box-Behnken design (BBD) [5]. Similarly, the effect of four factors on the compressive strength and abrasion resistance of Alkali-Activated slag (AAS) concrete was evaluated by the Taguchi method [6]. Likewise, Taguchi design of experiments was used for analyzing the effect of main factors on the compressive strength and ultrasonic pulse velocity of geo-polymer concrete production in high temperature [7]. To our best knowledge, no research has been done dealing with multi-objective optimization production with the aid of BBD. Thus, the aim of this paper is to optimize and determine influential factors on foamed concrete production process. Although the Taguchi model is a suitable method to optimize factors, RSM approaches are suitable for factors with continuous values, simple to train and learn, and more accurate to be presented. Moreover, the RSM set of methods make possible to differentiate between whether the related equation is linear or whether it appears quadratic. In addition, in order to determine triple factors based on input responses, BBD method is a unique solution.

The rest of the paper has been organized as follows: Section 2 presents the concept of RSM and its well-known design called BBD. Section 3 elaborates on the experimented procedure. The result and the optimum values of factors are given in Section 4. Final remarks and conclusion are provided in Section 5.

## 2. Theoretical basis

In many cases, organized experiments are needed to create some changes in system's controllable parameters in order to analyze the changes in the process outputs. The most important object of design of experiment (DOE) is the determination of effective factors in the way that outputs are close to their nominal values. Since there is no proved and scientific relationship between factors and responses in each problem, the empirical models are required to describe this relationship. To this end, a regression model is suggested to justify response changes based on input values. The surface of this equation in $k$-dimensional space shows the order of the equation. In First-order models, there is no sign of curvature and the equation is written as below:

$$y = \beta_0 + \sum_{i=1}^{k}\beta_i X_i + \sum_{i=1}^{k}\sum_{j=1}^{k}\beta_{ij} X_i X_j + \varepsilon_0 \quad (1)$$

where $\beta_i$and $\beta_{ij}$ are regression coefficients, $X_i$ represents the factors and $X_iX_j$ demonstrates interaction between factors and $\varepsilon_0$ is a measurement error in the process. However, in most cases, a curvature is observed in the surface. Therefore, a second or higher order model would be suitable for predicting the surface curve:

$$Y = \beta_0 + \sum_{i=1}^{k}\beta_i X_i + \sum_{i=1}^{k}\beta_{ii} X_i^2 + \sum_{i=1}^{k}\sum_{j=1}^{k}\beta_{ij} X_i X_J + \varepsilon_0 \quad (2)$$

Response surface methodology (RSM) is a technique that provides methods to determine the curve of this surface. Box-Behnken design was suggested to present a second-order model in a $k$-dimensional space. For instance, in case of three factors, the edge points in the middle of cube sides along with center points are tested [8–10] (see Fig. 1).

In this study, Box-Behnken model with three factors is used as statistical approach to predict a multi-objective surface which describes the relationship between three factors of foamed concrete production, and compressive strength, density and cost are listed as three responses. It should be noted that the criterion used for evaluating the response optimization is the desirability function. If the goal is to optimize a single response, the term individual desirability function is used, while in case of more than one response, composite desirability function is commonly applied. The definition of desirability function is different depending on whether the response should be maximized, minimized or whether the target value should be determined. For instance, if maximizing a response is desired, the desirability is calculated as below [10]:

$$\begin{aligned} & d_i = 0 \quad Y_i < L_i \\ & d_i = \left(\frac{(Y_i - L_i)}{(T_i - L_i)}\right)^{r_i} \quad L_i < Y_i < T_i \\ & d_i = 1 \quad Y_i < T_i \end{aligned} \quad (3)$$

where $T_i$ is the target value which is selected large enough for the $i$th response, $L_i$ is the lowest acceptable value for the $i$th response, $d_i$ is called desirability and $r_i$ is the weight of desirability function corresponding to the $i$th response.

If the importance of all responses is equal, the composite (overall) desirability is calculated via the below equation:

$$D = (d_1 \times d_2 \times \ldots d_n)^{1/n} \quad (4)$$

where the $n$ is the number of responses.

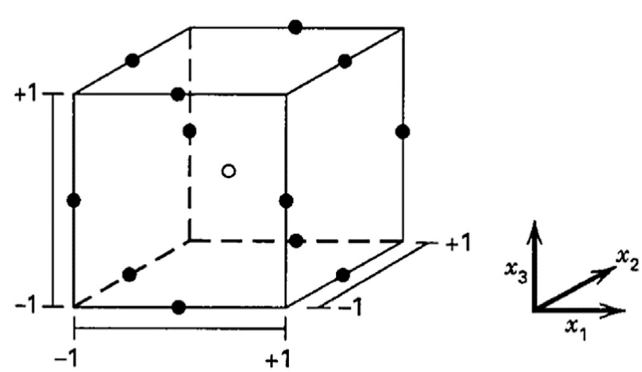


**Fig. 1.** Box-Behnken design for $k$ = 3.