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Refined statistical modeling for chloride permeability and strength of concrete containing metakaolin

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HIGHLIGHTS

- Optimize chloride permeability and strength was performed in concrete with MK.
- Total binder content, percentage of metakaolin, and W/B ratio were considered.
- Statistical models and design charts were developed.
- The developed models and charts are beneficial for mixture proportions prediction.

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ABSTRACT

An experimental investigation was conducted to develop design tools using refined statistical analysis to optimize chloride permeability and strength of concrete containing metakaolin (MK). The study adopts the design of experiments (DOEs) to test 53 concrete mixtures based on enhanced response surface method (RSM). Three factors were considered: total binder content (binder), percentage of metakaolin (MK%), and water-to-binder ratio (W/B). The mixtures were examined based on the rapid chloride permeability test (RCPT), chloride diffusion test, compressive strength (f_c), modulus of elasticity (MOE), splitting tensile strength (STS), flexural strength (FS), and cost of mixture per cubic meter. The developed statistical models and design charts are valid for concrete with W/B ratios ranging from 0.3 to 0.5, MK from 0% to 25%, and total binder content from 350 kg/m^3 to 600 kg/m^3. The results endorse that the obtained derived models and design charts are useful for understanding the influence of the key factors on concrete mechanical and durability properties. These models and design charts are beneficial for predicting and selecting the optimum mixture proportions for a given application in a simple and accurate way. This paper's recommendations can be of special interest to designers considering the use of concrete containing MK in structural applications.

1. Introduction

Optimizing concrete mixtures has become essential in recent years, with various supplementary cementing materials (SCM) and admixtures being added to concrete. Statistical design technique is an efficient tool for optimizing concrete mixtures as it provides statistical models, which helps researches to understand the interactions between parameters that have been modelled and optimized [1]. There are numerous models used for optimizing concrete mixtures such as response surface methodology (RSM), factorial design, and fractional factorial design [2–7]. Design of experiments method relies on analysis of variance [8,9]; this method selects a few points out of the full factorial set that can represent accurate information about the response space.

Central composite design (CCD) and face-centered composite design (FCCD) are RSM design techniques applied in numerous civil engineering fields [10–13]. CCD and FCCD are a compilation of mathematical and statistical techniques used for developing, refining, and optimizing processes, and can be used to evaluate the relative significance of numerous factors, even in complex interactions. Both CCD and FCCD methods divide the experimental space into three parts: the factorial part (2^k, where k = number of influencing factors), axial part, and central part [8,14]. The main difference between the two methods is the location of the axial points (Fig. 1). The sampling axial point in the CCD method is located outside the design space by distance $\propto = \sqrt[4]{2^m}$ (m = factorial factors), whereas in the FCCD method the axial points lay on the

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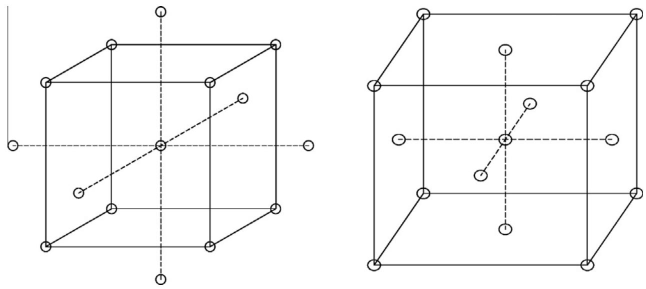

Fig. 1. CCD and FCCD point arrangement.

boundary of the design space. Fig. 1 shows the location of the points in both CCD and FCCD methods. The number of points for each method is fifteen: 8 vertices points, 6 axial points, and 1 central point.

Utilizing MK as SCM in concrete is receiving great attention nowadays. MK improves the mechanical and durability properties of concrete compared to concrete without SCM. MK also makes the concrete environmentally friendly as it does not emit CO_2 and requires lower manufacturing temperatures compared to cement. In precast concrete industry, mixtures with up 25% MK proved to have enhanced mechanical and durability properties [15–17]. According to previous studies, incorporating MK in concrete mixtures increases strength and rate of strength gain and improves the overall mixture durability [5,18,19]. Concrete mixtures containing 0–20% MK showed a noticeable increase in the compressive strength (f_c) [20,21]. The ideal MK replacement level was found to be approximately 20–25% and any further increase in the MK percentage showed no effect on the f_c [20,22,23]. On the other hand, adding MK was also found to improve the concrete splitting tensile strength (STS), flexural strength (FS), and modulus of elasticity (MOE) [20–22].

The prediction of chloride ingress in reinforced concrete structures has become a crucial part in service life prediction and the maintenance of new and existing structures [24–26]. The resistivity of concrete to chloride ingress is expressed by the chloride permeability property. The Assessment of chloride permeability can be performed using RCPT (ASTM C1202) and/or a chloride bulk diffusion test (ASTM C1556). The corrosion occurs when the chloride level at the rebar exceeds the normal threshold [27,28]. The addition of MK in concrete proved to reduce the chloride permeability and increase the pH of the mixture [29,30]. Therefore, mixtures containing MK can be expected to provide a high degree of protection against corrosion. However, the overall strength and durability of MK mixtures are greatly affected by the physical and chemical properties of the MK [18,31,32].

Limited research has been undertaken that considers the statistical analysis in optimizing the chloride permeability and strength of MK mixtures [33–36]. In addition, most of the available studies utilized a traditional statistical analysis with minimum number of points representing the response space. The main objective of this investigation was to utilize an enhanced statistical analysis to develop more precise models and design charts for concrete containing metakaolin. The variables were total binder content, water-to-binder ratio, and percentage of MK. The models' responses were rapid chloride permeability, chloride diffusion, compressive strength, modulus of elasticity, splitting tensile strength, flexural strength, and cost per cubic meter. Design of experiments approach was also used to present the most significant factors affecting each variable in the mixture and to develop prediction models for each test result. In addition, a numerical optimization tool was utilized to select an optimized mixture achieving the balance between high mechanical/durability properties and lower cost. This mixture was then tested experimentally using the same procedure to validate the prediction models.

2. Development of refined response surface method

Three factors were considered in the developed enhanced CCD model: total binder content, W/B ratio, and the percentage of MK. The effect of each factor was evaluated at five different levels corresponding to coded values of −1, −0.5, 0, +0.5, and +1 to establish nonlinear models (Eq. (1)). The developed CCD model in this investigation considered more points on the block surface than the commonly used points in standard CCD (Fig. 1). In this study a quadratic model was selected with 8 vertices points, 12 centers of edges, 6 constrain plane centroids, 8 axial check points, 18 interior points, and 1 overall centroid (Fig. 2). These points give a total of 53 points to develop the optimization models compared to 15 points using the standard CCD model (see Fig. 1). The developed models had three independent factors: X_1, X_2, and X_3. X_1 represents the total binder content, X_2 represents the W/B ratio, and X_3 represents the percentage of MK. The derived statistical models are valid for concrete mixtures made with total binder content ranging from 350 kg/m^3 (−1) to 600 kg/m^3 (+1); W/B ratio from 0.3 (−1) to 0.5 (+1); and percentage of MK from 0% (−1) to 25% (+1). The selected range for each of the binder content, W/B ratio, and MK percentage were chosen based on the literature and practical considerations and to cover a wide range of possible mixture proportions.

The coded values are expressed according to Eq. (1):

$$\textit{Coded Value} = \frac{\text{absolute value} - \text{central value}}{0.5 \times \text{range between maximum and minimum values}} \quad (1)$$

A polynomial function was fitted to correlate independent factors and responses using Eq. (2). The measured responses were compressive strength (Y1), flexural strength (Y2), modulus of elasticity (Y3), splitting tensile strength (Y4), rapid chloride permeability (Y5), chloride diffusion coefficient (Y6), and cost per cubic meter (Y7).

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ij} X_i X_j + \sum \beta_{ii} X_i^2 \quad (2)$$

where Y is the predicted response, X_i is the independent factor, β_0 is the constant coefficient of the model (intercept), β_i (i = 1, 2, 3), β_{ij} (i = 1, 2, 3; j = 1, 2; $i > j$), and β_{ii} represents linear, interaction, and quadratic effect of the model, respectively.

A commercially available program for experimental design using statistical analysis method was used to analyze the outcomes from each test [37]. This program performs nonlinear regression analysis for each response (test result) based on the input values (variables). Eventually, the program yields to equations of the response and obtains response surface diagrams. The developed equations were based only on the most significant variables (factors) and their interactions. The equation may be linear or nonlinear depending on the behavior of the response throughout the range of variables. Linear equations contain main variables and their interactions, while nonlinear equations include higher-order variables (quadratic or cubic). The significance of the variables and their connections was determined after compiling the analysis of variance (ANOVA). The analysis of variance tests the probability values (Probability > F); the factor is significant if its probability value is less than 0.05 [8]. In addition, the degree of significance among the significant factors can be determined based on the F-value for each factor. The factor with a higher F-value is considered more significant than factors with lower F-values. On this basis, the significant variables for each response were selected to form the prediction equations. These equations exhibited some coefficients, which depend on the contribution of each factor.