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Developing of non-linear weight functions for mix design optimization of cementitious systems

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ABSTRACT

Mix design in production cementitious materials is of importance where selection value of each parameter has a critical effect on final properties of material. In the present work, a new method has been developed to determine the effect of each considered mix design factor on output properties. A specific property can be related linearly to factors of mix design through normalized nonlinear weight functions. The proposed procedure was applied on two different mix designs available in the literature. The first analysis was conducted on ordinary Portland cement based concrete specimens to analyze the importance of each factor on their compressive strength. The second one was conducted on a geopolymeric system to analyze compressive strength. For both systems, the factors were divided into sensitive and non-sensitive where sensitive factors were suggested to be considered with more attention in mix design procedure.

1. Introduction

Production of a constructional specimen from cementitious materials requires specific attention on mix design procedure. Nowadays, besides using the four basic components of ordinary Portland cement (OPC) based concrete specimens including cement, water, natural fine aggregates and natural coarse aggregates, other various materials are added to the mixture such as fly ashes [1–3], slags [4,5], pozzolanic materials [6], fibers [7], silica fume [8], agricultural ashes [9] and so on. On the other hand, geopolymers, cement-free specimens which are increasingly developed in constructional industry, are made from different aluminosilicate sources such as fly ash [10–12], slags [13,14] and metakaolin [15]; their alkali activators made from various constituents. Incorporating of several factors in mix design of a specific structure is hard and engineers are forced to find their best required property by trial and error. Although some attempts have been made to propose a mix design by design of experiment methods (DOE), such as Taguchi method [16], to determine the effect of each factor on final properties of concrete specimens, it is not possible to state that these methods can definitely reveal the most accurate result. Especially when there are several factors, number of experiments required is too many while DOE methods decide on results by proposing only a few experiments. Therefore, step by step mix design is utilized to develop a mixture proportion without considering the sensitivity of choosing the range of some factors.

Yu et al. [7] developed a mix design procedure for evaluation workability, air content, porosity, and flexural and compressive strengths of ultra-high performance fiber reinforced concrete. The materials used were OPC, limestone and quartz fillers, micro sand as fine aggregate, sand 0–2 as coarse aggregate, silica fume, polycarboxylate superplasticizer, steel fibers and water. They have followed the modified Andreasen and Andersen particle packing model to achieve a densely compacted cementitious matrix. Although using the amount of OPC, water to binder ratio, and the content of fine and coarse aggregates are standardized for several mixtures, using other constituent materials

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may cause several problems to present the most accurate mixture. Kanadasan and Razak [17] presented a mix design methodology for using palm oil clinker (POC) aggregates in self compacting concrete. The mix design procedure was carried out by constant ratio of several critical parameters and only changing the content of POC. Although a straightforward method by selecting a range of constant POC ratios has been developed, one may observe that in some cases, further experiments are required to determine the effect of each POC contents on properties of concrete. Kupaei et al. [18] have presented mix design procedure for evaluating compressive strength of oil palm shell (OPS) geopolymer lightweight concrete. Their variables include fly ash, sand, OPS, water, superplasticizer and alkali activator molarity. They have conducted 24 experiments on several mixtures and on the basis on the specimen with highest compressive strength, 8 additional experiments have been carried out. It seems that for this huge number of parameters and their range, an analysis of the experiments is required to determine the sensitive factors and their influence on final properties. Pacheco-Torgal et al. [19] conducted a mix design procedure to evaluate compressive strength of tungsten mine waste geopolymeric binder. Their variables were $Ca(OH)_2$ content, Sodium hydroxide concentration, H_2O/Na_2O molar ratio, curing time, sodium silicate to sodium hydroxide weight ratio and water to binder ratio. Lim et al. [20] used several mixtures to evaluate compressive strength and workability of high performance concrete. Their factors were water to binder ratio, water content, fine aggregate ratio, silica fume replacement ratio and superplasticizer content. Although their main focus in not on mix designs evaluation, it could be suitable source as a case study in the present work.

In the present work, a methodology has been developed to determine the role of each factor considered in a specific mix design program. For each factor, a non-linear normalized weight function can be presented which determines its importance at lower and upper bounds. Factors that their weight function could not be presented as an accurate function are called sensitive and their range of mixture proportion is suggested to be considered with more attention. Two case studies have been selected from the literature [19,20] to evaluate the performance of the suggested methodology.

2. Methodology

For a mix design procedure consisting of n factors with the target of K (e.g. compressive strength), a linear function can be written between the factors and target through utilizing weight functions, w'':

$$w''_1 \cdot F_1 + w''_2 \cdot F_2 + w''_3 \cdot F_3 + \cdots + w''_i \cdot F_i = K \quad i = 1 \ldots n \tag{1}$$

There is not any simple method to solve the equation even by specified input and target data. One possible way to solve the equation is considering similar value for inputs. Then it can be concluded that all inputs have similar weights. Therefore:

$$w''_1 + w''_2 + w''_3 + \cdots + w''_i = K \quad i = 1 \ldots n \tag{2}$$

or in the other form:

$$\sum_{i=1}^{m} w''_i = K \quad i = 1 \ldots n \tag{3}$$

where

$$w'_i = \frac{w''_i}{F_i} \tag{4}$$

The simplest solution for Eq. (3) will be:

$$w''_i = \frac{K}{n} \tag{5}$$

By substituting Eqs. (4) into (5), the corresponding weights can be written as:

$$w''_i = \frac{K}{n \cdot F_i} \quad i = 1 \ldots n \tag{6}$$

Normalized weight function, w_i, on the basis of scoring the sum of weights to 100 can be written as following:

$$w_i = \frac{w''_i}{\sum_{i=1}^{n} w''_i} \quad i = 1 \ldots n \tag{7}$$

For a mix design procedure consisting of m mixture proportion and n factors, the matrix form of the normalized weight functions can be written as:

$$\begin{bmatrix} F_{11} & F_{12} & \cdots & F_{1n} \\ F_{21} & F_{22} & \cdots & F_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ F_{m1} & F_{m2} & \cdots & F_{mn} \end{bmatrix}_{m\times n} \cdot \begin{bmatrix} w_{i1} \\ w_{i2} \\ \vdots \\ w_{ij} \end{bmatrix}_{n\times 1} = \begin{bmatrix} K_1 \\ K_2 \\ \vdots \\ K_m \end{bmatrix}_{m\times 1}, \quad i = 1 \ldots n, \; j = 1 \ldots m \tag{8}$$

It is worthwhile to mention that using quantities of the input variables may cause error in the final results. For example, during mix design of a concrete mixture, the total content of fine and coarse aggregates is about 1700–1900 kg/m^3 while the amount of superplasticizer varies around 5–30 kg/m^3. By using Eq. (5), the weight of superplasticizer will be much higher than the weight of aggregates. To overcome this problem, it is suggested that a mixture is considered as the reference mixture, and input and target variables are considered as the variation of inputs and target with respect to the reference mixture as following:

$$\begin{bmatrix} \Delta F_{11} & \Delta F_{12} & \cdots & \Delta F_{1n} \\ \Delta F_{21} & \Delta F_{22} & \cdots & \Delta F_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \Delta F_{m1} & \Delta F_{m2} & \cdots & \Delta F_{mn} \end{bmatrix}_{m\times n} \cdot \begin{bmatrix} w_{i1} \\ w_{i2} \\ \vdots \\ w_{ij} \end{bmatrix}_{n\times 1} = \begin{bmatrix} \Delta K_1 \\ \Delta K_2 \\ \vdots \\ \Delta K_m \end{bmatrix}_{m\times 1}, \quad i = 1 \ldots n, j = 1 \ldots m \tag{9}$$

where ΔF_{ji} and ΔK_j are the change of input and target data with respect to the reference mixture respectively.

Several functions can be plotted to consider the effect of each factor on mix design procedure including the weight of each factor versus the sample designation, the weight versus the variation of each factor and the weight of each factor versus the target property. To evaluate these plots, two case studies will be adopted in the following.