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Prediction of lower and upper bounds of elastic modulus of high strength concrete

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Abstract

Modulus of elasticity is particularly important in the analysis and design of reinforced concrete structures. Several predictive formulas are recommended in different codes to find out elastic modulus of high strength concrete (HSC). This paper presents a new approach for the prediction of the elastic modulus of HSC using fuzzy models. The fuzzy models are advantageous with their ability to describe knowledge in a descriptive way in the form of simple rules by using linguistic variable only. The theory of fuzzy sets is examined in the paper and the study intensified around fuzzy modeling as a method to predict elastic modulus of HSC. A fuzzy logic algorithm was devised for estimating the elastic modulus of HSC from compressive strength. The method was also found useful to predict lower and upper bounds of elastic modulus of HSC easily where more realistic results can be obtained.

Keywords: Fuzzy logic; High-strength concrete; Compressive strength; Elastic modulus

1. Introduction

Technological developments enabled continuous increase of strength of materials and improvement of some other material properties such as quality and durability. The use of high strength concrete (HSC) is preferred not only for economical design, but also for its durability which is one of the main concerns of material engineering, especially when long-term service life and sustainability are required. In structural engineering, elastic modulus of concrete is useful for serviceability limit states, which may be critical for slender and thin sections of HSC structures. In designing of these HSC structures, it is necessary to improve the available models for determining elastic modulus.

Due to the different characteristics of high strength concrete, some design procedures traditionally used in normal strength concrete (NSC) structures have to be changed. When HSC began to be developed, several relationships were proposed to predict HSC elastic modulus from compressive strength. Some of the relationships for HSC are given as follows: ACI 363 [1]

$$E_c = 4.730(f_c)^{1/2} \tag{1}$$

CEB [2]

$$E_c = 21.500(f_c/10)^{1/3} \tag{2}$$

NS 3473 [3]

$$E_c = 10.000(f_c)^{0.3} \tag{3}$$

where f_c and E_c are expressed in MPa and in GPa, respectively.

Many researchers pointed out the importance of determination of the elastic modulus [4,5]. The effect of size and mineralogical nature of the aggregates on high strength concrete carried out with the objective of determining [6,7].

It can be expected that the relationship between elastic modulus and compressive strength of concrete is affected by the composition of the concrete. Therefore, it is difficult

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to state a certain relationship that is always valid for the elastic modulus of concrete. Besides, it is known that the aggregate has a significant effect on strength and elastic modulus of HSC. From this point of view, for a given concrete strength, it is possible that different elastic moduli would be obtained from the equations recommended by ACI [1], CEB [2] and NS 3473 [3] codes. As a result, several researchers [4] have stated that the relationships recommended by some codes to predict elastic modulus of HSC are not accurate.

HSC elastic modulus estimations derived from compressive strength can be obtained in the literature either through linear equations or original power functions. There is a gap in the literature for the prediction of elastic modulus through fuzzy algorithm. In this paper, such an approach is presented to predict elastic modulus of HSC. This study aims to calculate elastic modulus together with its lower and upper bounds of HSC by using fuzzy algorithm. It is suggested that the lower and upper bounds of elastic modulus should be taken into account where almost all other possible elastic moduli recommended by codes and other investigators are included. This procedure is more realistic compared to using only one elastic modulus of HSC. Moreover considering lower and upper bounds of elastic modulus brings some advantages such as covering the differences due to elastic moduli in the analysis of reinforced concrete structures.

In this study, numerical investigation is carried out and the lower, upper and fuzzy results are compared to those of test data from the literature. The numerical results reveal a good agreement between the test and fuzzy method yields. This algorithm can be extended to obtain more accurate elastic modulus results by taking into consideration other parameters affecting elastic modulus of HSC.

2. Fuzzy sets and logic

The fuzzy logic concept provides a natural way of dealing with problems in which the source of imprecision is an absence of sharply defined criteria rather than the presence of random variables. The fuzzy approach considers cases where linguistic uncertainties play some role in the control mechanism of the phenomena concerned. Herein, uncertainties do not mean random, probabilistic and stochastic variations, all of which are based on numerical data. In this study, however, a simplified view of linguistic variables of concrete compressive strength and modulus of elasticity of concrete is adopted. The fuzzy logic definition in the following is tailored to the application to elastic modulus of high strength concrete modeling which in many ways is very similar to the established use of fuzzy logic in the control of dynamic systems, also known as "fuzzy logic control". In both contexts, fuzzy propositions, (i.e. IF–THEN statements) are used to characterize the state of a system and the true value of the proposition is a measure of how well the description matches the state of the system.

The key idea in fuzzy logic is the allowance of partial belonging of any object to different subsets of the universal set instead of belonging to a single set completely. Partial belonging to a set can be described numerically by a membership function (MF) which assumes values between 0 and 1 inclusive. Even if the measurements are carefully carried out as crisp quantities they can be fuzzified. Furthermore, if the form of uncertainty happens to arise because of imprecision, ambiguity or vagueness, then the variable is fuzzy and can be represented by a MF [8].

In order to simplify the calculations, usually the MF is adopted as linear in practical applications.

In the fuzzy inference method sets of corresponding input and output measurements are provided to the fuzzy system which learns how to transform a set of inputs to the corresponding set of outputs through a Fuzzy Associative Map (FAM) which is also called the Fuzzy Associative Memory [9]. Fuzzy logic does not provide a rigorous way for developing or combining fuzzy rules which can be achieved through many ways.

The fuzzy methodology application can be achieved through the fuzzy rules as outlined below:

The input and output variables are divided into a number of subsets with simple triangular fuzzy MFs. Generally, there are n^m fuzzy rules where n and m are the numbers of subsets and input variables, respectively. A fuzzy rule base can be achieved step-by-step from sets of input and output data as follows:

1. Try to model the problem with a minimum number of input variables.
2. Divide the range of each input variable into a number (usually 4–8 in practice but into m in general) of parts to give fuzzy subsets each with a triangular MF. Theoretically, the optimum number of fuzzy subsets can be found by minimizing the total squared error between the observations and predictions.
3. For each data point corresponding membership values are computed in each fuzzy rules.
4. Compute the weight of each rule for data point m by multiplying the membership values that correspond to that rule and squaring the result.
5. Store the output along with the complete set of rule weights.
6. Repeat the same steps for all the other data points.
7. Compute the weighted average [8,10,11].

3. Fuzzy algorithm for prediction of elastic modulus of high strength concrete

It is a fact that the modulus of elasticity increases with an increase in the compressive strength of concrete, but there is no agreement on the precise form of the relationship. The modulus of elasticity of concrete is affected by the modulus of elasticity of the aggregate and by the volumetric proportion of aggregate in the concrete. Several