Available online at www.sciencedirect.com
SCIENCE DIRECT
Cement and Concrete Research 35 (2005) 1531–1538
Cement and Concrete Research

A new way of prediction elastic modulus of normal and high strength concrete—fuzzy logic

Fuat Demir
Suleyman Demirel University, Turkey

Received 18 January 2004; accepted 17 January 2005

Abstract

In this paper, the theory of fuzzy sets, especially fuzzy modeling is discussed to determine elastic modulus of both normal and high-strength concrete. A fuzzy logic algorithm has been devised for estimating elastic modulus from compressive strength of concrete. The main advantage of fuzzy models is their ability to describe knowledge in a descriptive human-like manner in the form of simple rules using linguistic variables only. On the other hand, many parameters will be effected and elastic modulus can be taken into account easily by using the proposed fuzzy model.

Keywords: Fuzzy logic; Concrete; Compressive strength; Elastic modulus

1. Introduction

Ideally, the elastic modulus is measured directly on concrete samples under compression by recording the load–deformation curve, but from an experimental point of view, this is not always easy. When compared with compressive strength measurements carried out to characterize the compressive strength f_c, this testing procedure is much more complicated and time-consuming. To avoid the demanding and time-consuming direct measurements of elastic modulus E_c, engineers and researchers have tried to find some shortcuts to enable them to predict the elastic modulus of concrete using either a theoretical or an empirical approach. In latter case, which is most widely used, the modulus of elasticity is usually expressed as a function of compressive strength. On the other hand, different national building codes propose various formulas for normal strength concrete (NSC) and high strength concrete (HSC). A lot of relationships for NSC are given as follows.

ACI 318-95 [1]

$$E_c = 4.73(f_c)^{1/2}$$

TS-500 [2]

$$E_c = 3.25(f_c)^{1/2} + 14$$

in which relationships f_c and E_c are expressed in MPa and in GPa, respectively. When HSC began to develop, a number of attempts were made to see whether the existing relationship could be used to predict HSC modulus of elasticity that had to be developed. For example American, European, and Norwegian committees on high strength concrete propose the following relationships:

ACI 363 [3]

$$E_c = 3.32(f_c)^{1/2} + 6.9$$

CEB90 [4]

$$E_c = 10(f_c + 8)^{1/3}$$

NS 3473 [5]

$$E_c = 9.5(f_c)^{0,3}$$

in which relationships f_c and E_c are expressed in MPa and in GPa, respectively.

Due to different characteristics of high strength concrete, for designing structures made of it, some design procedure traditionally used in normal strength concrete structures have to be changed. For this reason, determination of elastic properties of concrete has become very important from a

0008-8846/$ - see front matter
doi:10.1016/j.cemconres.2005.01.001

design point of view when the deformations of the different structural elements of a structure have to be calculated. Many authors have pointed out the importance of the determination of the elastic modulus [6,7]. In addition, several studies [8–10] on high strength concrete have been developed with the objective of studying the effect of parameters on elastic properties of high strength concrete.

In this paper, a new fuzzy approach has been presented to predict elastic modulus of both NSC and HSC. Numerical investigation is carried out and the fuzzy results are compared with those of test data and some other available in literature. Numerical results reveal a good agreement between the test and fuzzy results. To have an objective comparison of the performance of the models against the experimental results, the error measure of the root mean square error (RMSE) was computed for each model. The variances were computed for each model and experiment.

2. Fuzzy sets and logic

The concept of "fuzzy set" was introduced by Zadeh [11], who pioneered the development of fuzzy logic instead of Aristotelian logic which has two possibilities only. Fuzzy logic concept provides a natural way of dealing with problems in which the source of imprecision is the absence of sharply defined criteria rather than the presence of random variables. 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 the numerical data. Zadeh has motivated his work on fuzzy logic with the observation that the key elements in human thinking are not numbers but levels of fuzzy sets. Further he saw each linguistic word in a natural language as a summarized description of a fuzzy subset at a universe of discourse representing the meaning of this word. In consequence, he introduced linguistic variables as variables whose values are sentences in a natural or artificial language [12]. 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 sequel is tailored to the application of elastic modulus of normal and 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 truth value of the proposition is a measure of how well the description matches the state of the system. Fuzzy logic has been developing since then and is now being used especially in Japan for automatic control for commercial products such as washing machines, cameras and robotics. Many textbooks provide basic information on the concepts and operational fuzzy algorithms [13–17]. In several research, fuzzy approach has been used [18,19].

The key idea in fuzzy logic is allowance of partial belongings 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 which assumes values between 0 and 1 inclusive. For instance Fig. 1 shows a typical membership function for small, medium and large class size in universe, U. Hence, these verbal assignments are fuzzy subsets of the universal set. In this figure, set values less than 2 are definitely "small"; those between 4 and 6 are certainly "medium; while values larger than 8 are definitely "large". However, intermediate values such as 2.2 partially belong to the subsets "small" and "medium". In fuzzy terminology 2.2 has a membership value of 0.9 in "small" and 0.1 in "medium", but 0.0 in "large" subsets. The literature is rich with references concerning the ways to assign membership values or functions to fuzzy variables. Among these ways are intuition, inference rank ordering, angular fuzzy sets, neural networks, genetic algorithms, inductive reasoning, etc. [16]. Especially, the intuitive approach is used rather commonly because it is simply derived from capacity of humans to develop membership functions through their own innate intelligence and understanding. Intuition involves contextual and semantic knowledge about an issue; it can be also involve linguistic truth values about this knowledge [15].

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 membership function. Unlike the usual constraint where, say, the variable in Fig. 1 must not exceed 2, a fuzzy constraint takes the form as saying that the same variable should preferably be less than 2 and certainly should not exceed 4. This is tantamount in fuzzy sets terms that values less than 2 have membership of 1 but values greater than 4 have membership of 0 and values between 2 and 4 would have membership between 1 and 0. In order to simplify the calculations, usually the membership function is adopted

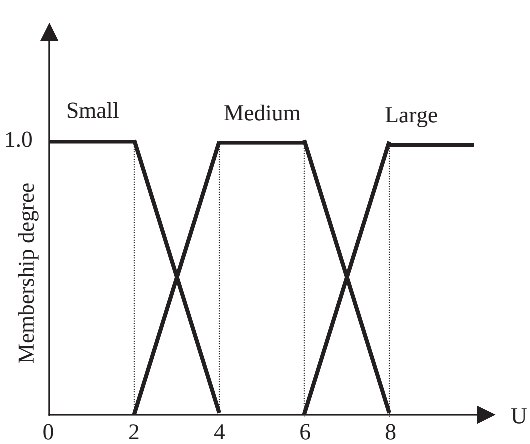

Fig. 1. Fuzzy subsets.