

# Fuzzy Logic Model for the Prediction of Compressive Strength of Cement Mortars

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**Abstract** Microstructural formation was related to the strength values of cement mortars, in the scope of this study. The established relationship was modeled by using fuzzy logic prediction model. Pore area, unhydrated part and hydrated part of cement mortars were addressed for microstructural investigations. These parameters were taken into account as area ratios for each. Area ratios of all microstructural parameters were correlated to compressive strength values of cement mortars. Established fuzzy logic prediction model indicates that the correlation between predicted and measured values of compressive strength of cement mortar represents a strong relationship for the investigated parameters. The study indicates that determination of only three parameters (Pore area, unhydrated part and hydrated part of cement mortars) is sufficient enough to represent the relationship of microstructural formation-compressive strength confidently. The results show that the fuzzy logic can be used effectively to predict compressive strength of cement mortars.

**Keywords** Fuzzy logic, Microstructure, Compressive strength

## 1. Introduction

Nowadays, microstructural characteristics and properties of engineering materials can be investigated more easily due to improved computer technology and computational capacities. Furthermore, engineers and scientists have great capacity to realize and associate inner structure with macro properties such roughness, strength and abrasion by using computational software and reasoning methods. Having this knowledge of the microstructural evolution of engineering materials at early age bring talent for forecasting of ultimate performance of these materials. Cementitious materials such as concrete, cement mortars, repairing materials and such isolation ones are also most used engineering materials. Determining microstructural properties of cementitious materials is important to predict their ultimate performance such as strength and durability.

Image analysis of micrographs of cementitious materials are performed to quantify the microstructure of cement pastes for determination of porosity, pore structure and phases such as undifferentiated hydration products and anhydrous cement content [1-5].

Compressive strength is one of the most important properties of cementitious materials in their service life [6]. Generally, compressive strength increases linearly with the

density. However, many other factors such as; pore size distribution, micro cracks, interface, etc., are also important factors that determine mechanical properties of cementitious materials [7]. In order to establish a relationship between pore structure, hydration degree and compressive strength, it is necessary to use current experimental technologies and analyze their results with reasoning methods such as fuzzy logic.

As stated by this, polished section investigations of cementitious specimens by microscopy techniques have become more popular. Polished specimens investigation has a great capacity on establishing the relationship between microstructure and macro properties by quantitative measures. Microscopy applications improve the ability to characterize the microstructure of cement mortar and concrete, and helps in investigating effects of admixtures, determining durability problems and service life duration [8].

Since the debut in the early of 1980, SEM micrographs under backscattered electron (BE) mode have shown a great potential to investigate cementitious materials [9]. This technique has some benefits such as; using flat sections representing the specimen better than fractured sections, having more magnification ratios, allowing the segmentation of phases more easily [6]. BE mode uses the electrons with high energy. Contrasts in BE mode imaging are originated by atomic numbers of microstructural phases [8]. Unhydrated cement part, calcium hydroxide (Ca(OH)<sub>2</sub>) part, aggregate are classified to brightest to darkest, respectively [10].

In this study, the relationship between microstructural

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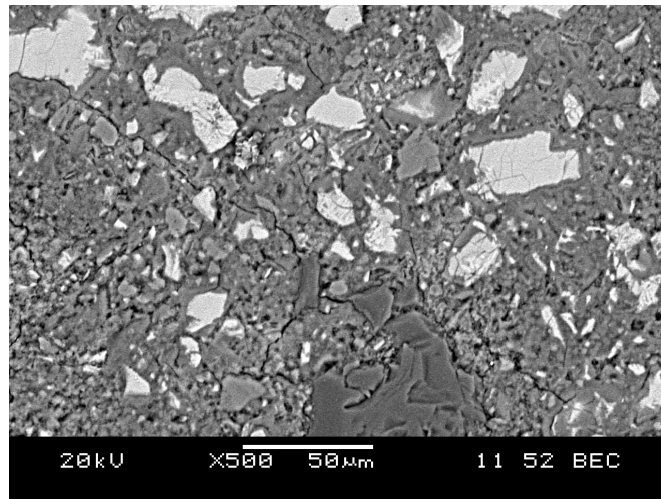
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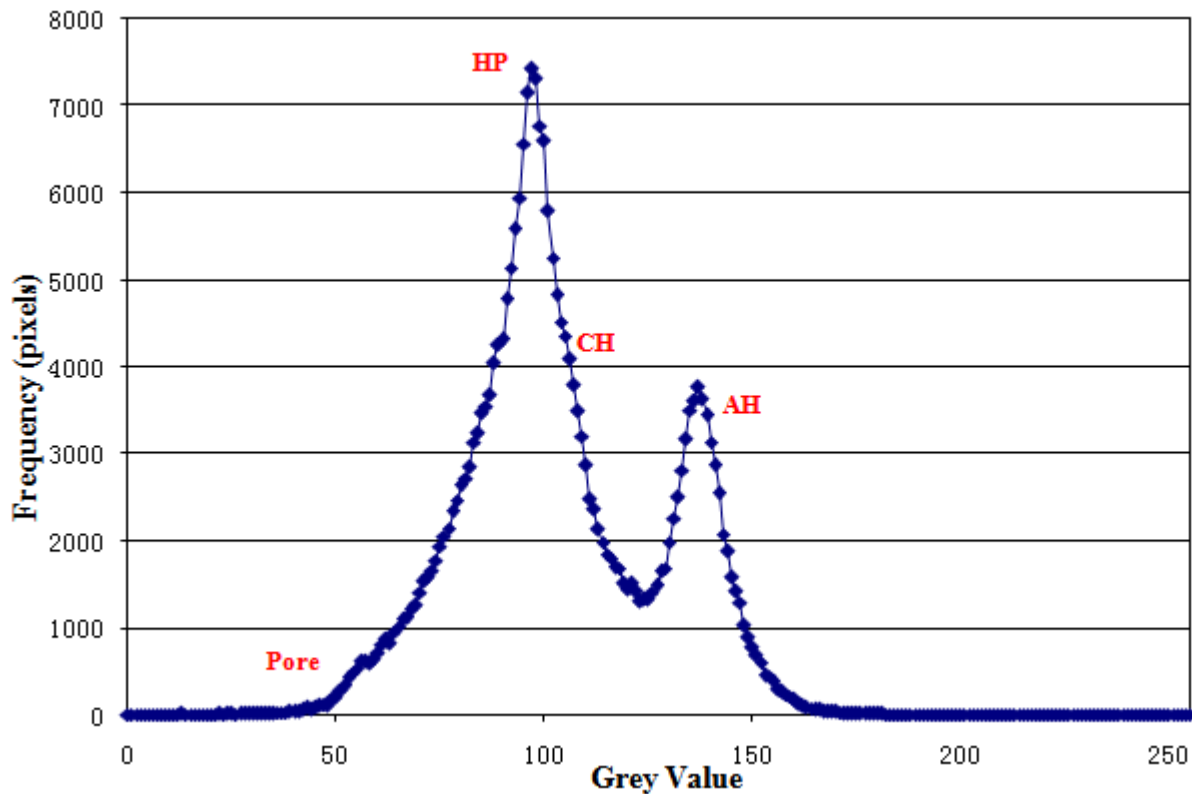
properties of cement mortars and compressive strength has been established by using fuzzy logic prediction model. Polished sections of cement mortars were prepared at different ages to determine the effects of microstructural phase formation on the mechanical properties of cement mortars.

There are many advantages of using developed fuzzy logic prediction technique one of which is its simplicity and its flexibility. The developed prediction technique can handle the problem with imprecise and incomplete data, and it can

model nonlinear systems. When the system changes, the developed fuzzy logic technique can produce a better solution than conventional control techniques. Developed fuzzy logic predicting model can also be compared with the predicting models that use artificial neural networks. With the developed model, fuzzy logic system enables the inclusion of linguistic knowledge in a systematic way. But in the predicting models that use artificial neural networks, inclusion of linguistic knowledge is prevented and hence learning phase is prolonged.



(a)



(b)

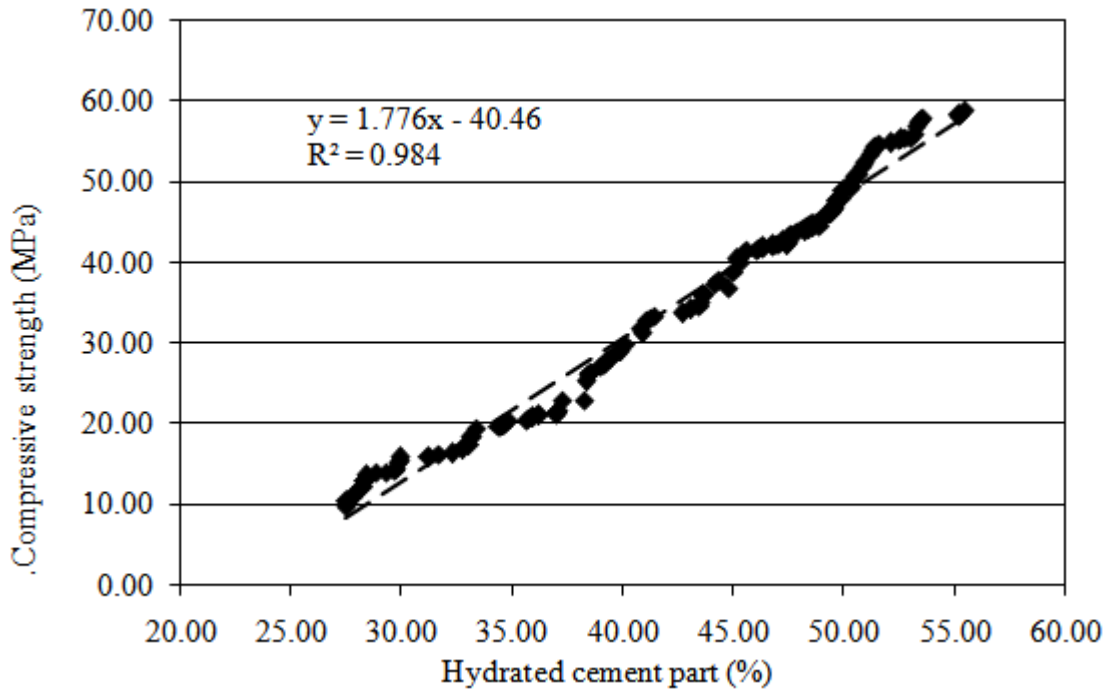
Figure 1. (a) Micrograph and (b) Histogram of cement mortar by 500X magnification

## 2. Experimental Study

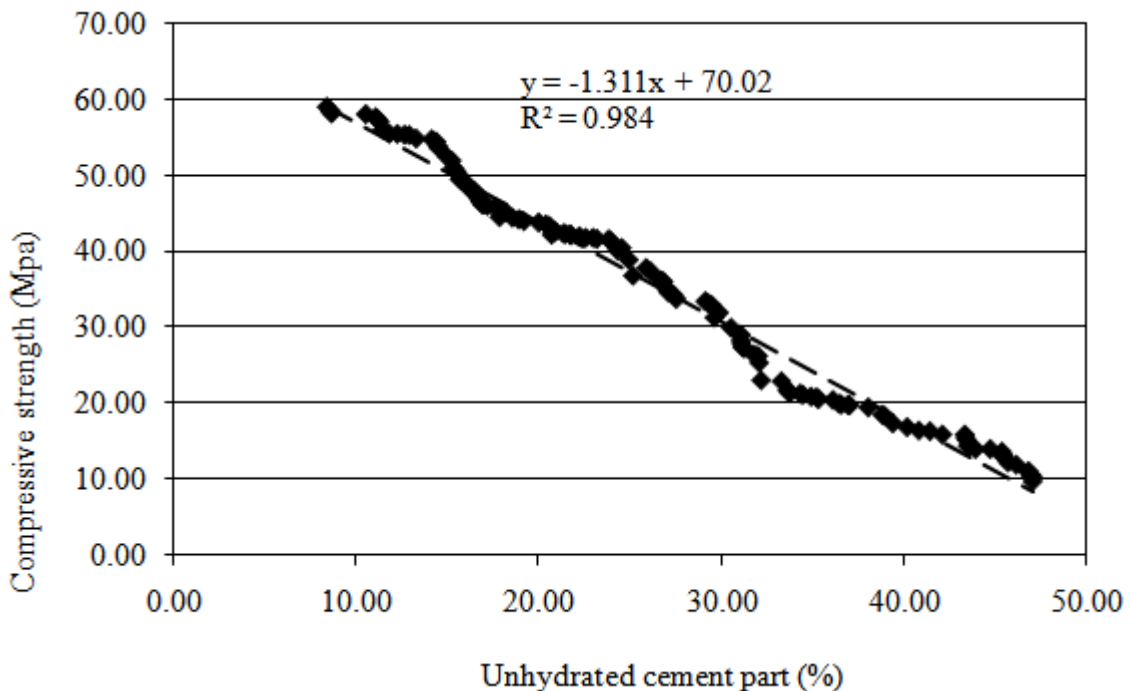
Cement mortars were prepared by incorporation of chemical admixtures. Two types of admixtures are lignin based modified polymer, and others are naphthalene sulphonate based and modified phosphate based admixtures. Therefore two different types of cement (CEM I 42,5 R and CEM II A-M 42,5 R) were used. Different types of cements and admixtures were used to form different kind of inner

structures. Compressive strength properties of cement mortars at the ages of 1, 2, 7, 28 and 90 days were found on the 50 mm cube.

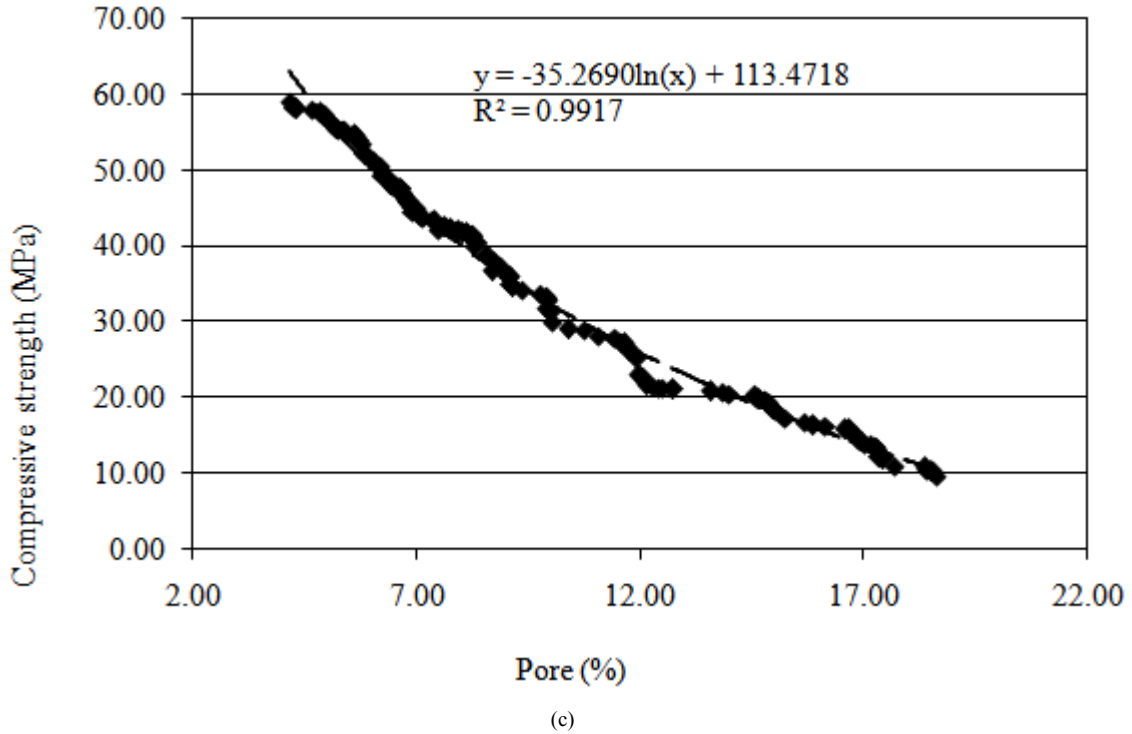
All tests were performed in the laboratory conditions such as  $20 \pm 2^\circ\text{C}$  and 75-80% relative humidity. Compressive strength properties of cement mortars were found on the 50 mm cube. Microstructural investigation is the topic of the second part of the experimental studies.



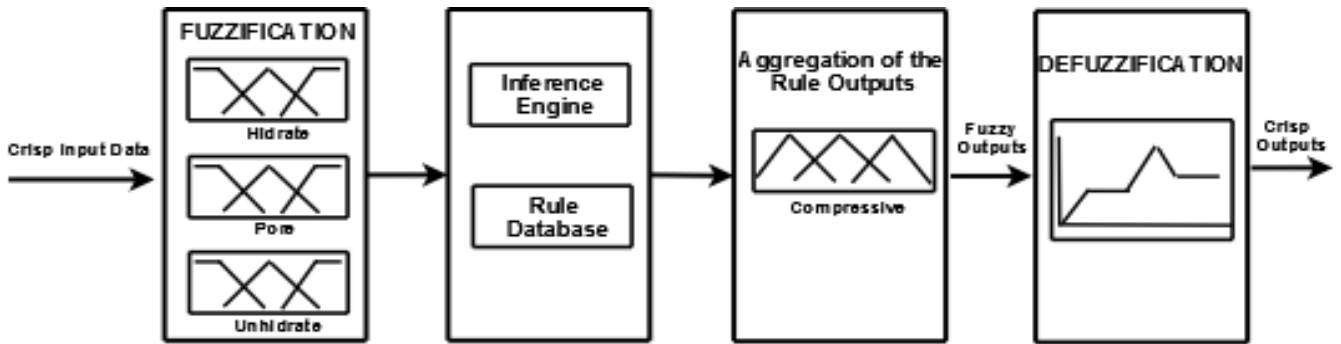
(a)



(b)



**Figure 2.** (a) Hydrated cement part amount-compressive strength (b) Unhydrated cement part amount-compressive strength (c) Pore amount-compressive strength relationship



**Figure 3.** Block diagram used for the proposed fuzzy model

To minimize the effects of cutting specimens, some of the mixtures were cast into plastic molds. After 1, 2, 7, 28 and 90 days, hydration processes of the mixes were delayed by submerging specimens into alcohol ispropylique for five days. Before microstructure studies, the specimens were covered by a polyester film, and then the surface of each specimen was polished. Each specimen was sanded by 600 and 1200 grit sandpapers. After sanding, each specimen was polished by 0.25, 1, 3 and 9 μm diamond paste for 120 s [11].

The phases in a polished section can be segmented by their grey level thresholds in the micrograph of cementitious materials. The grey level values of phases compose separate peaks in the grey level histogram (Figure 1) with their heights proportional to the relative fractions of each phase [6].

Compressive strength depends on pore characteristics and hydration process of the cementitious materials. Pore

characteristic such as pore area ratio has been accounted in the analyses. Therefore, hydrated and unhydrated part indicating hydration degree, were taken in to account. These parameters were used to define the whole characteristics of parameters being effective on strength. The results of image analysis and the relationship with compressive strength were given below.

### 3. Fuzzy Logic Prediction Model

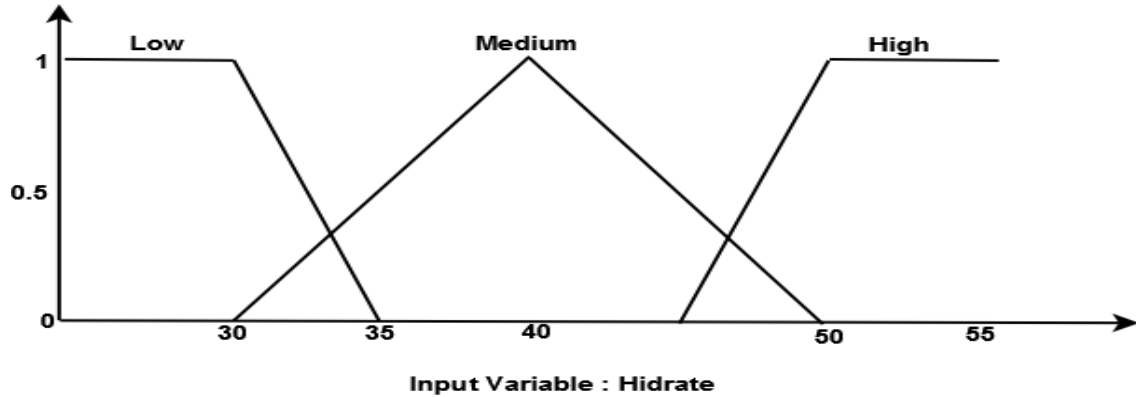
Fuzzy Logic which is first developed by the mathematician Lotfih A. Zadeh in 1965, deals with the imprecision and uncertainty reasoning rather than fixed and exact one [12]. In contrast with traditional logic, such as Boolean Algebra which only recognizes 0 and 1 and is insufficient to many real world applications, fuzzy logic system recognizes values that ranges in degree between 0

and 1 [13, 14].

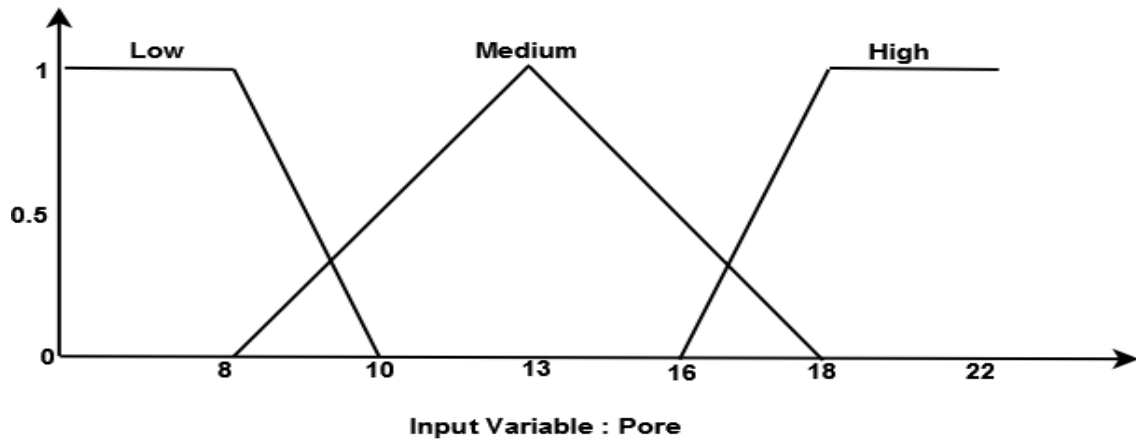
A fuzzy logic system has four main components namely, fuzzification, fuzzy rule base, fuzzy inference engine and defuzzification. In fuzzification step, a set of input data is converted to a fuzzy set by using fuzzy linguistic variables and membership functions. Membership function is a graphical representation of the magnitude of participation of each input. It associates a weighting with each of the inputs that are processed and defines functional overlap between inputs, and finally determines an output response [15]. Following this, an inference is made based on a set of fuzzy

rules which uses the input membership values as weighting factors to determine their influence on the fuzzy output sets of the final output [15]. Finally in defuzzification step, the resulting fuzzy output is mapped to a crisp output. The block diagram of the proposed fuzzy logic model is shown in Figure 3.

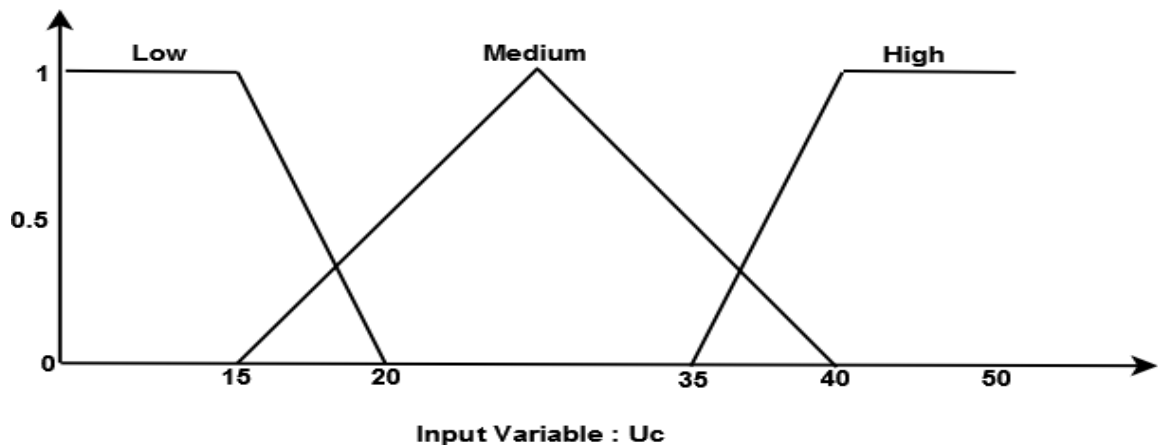
Three input parameters namely; hidrate, pore and unhydrated area ratios were used as input and compressive strength values were used as output parameters. These input and output parameters are firstly converted to a fuzzy set using membership functions as shown in Figure 4.



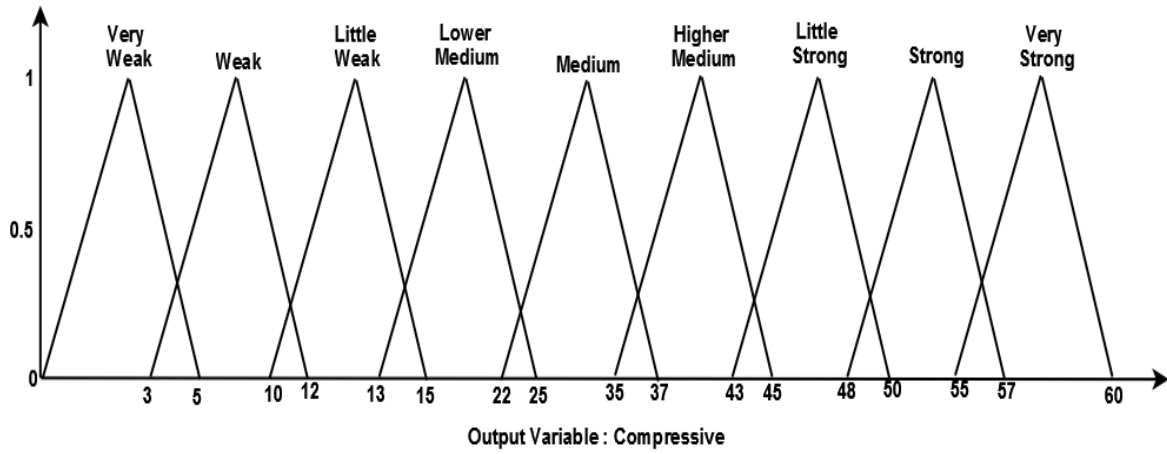
(a)



(b)



(c)



(d)

Figure 4. Membership Functions of the parameters (a) Hidrate (b) Pore (c) Unhydrated (d) Compressive

Table 1. Fuzzy Rules of the System

Hidrate	Unhidrate	Pore	Compressive
Low (0)	Low (0)	Low (0)	Medium (4)
Low (0)	Low (0)	Medium (1)	Lower_Medium (3)
Low (0)	Low (0)	High (2)	Little_Weak (2)
Low (0)	Medium (1)	Low (0)	Lower_Medium (3)
Low (0)	Medium (1)	Medium (1)	Little_Weak (2)
Low (0)	Medium (1)	High (2)	Weak (1)
Low (0)	High (2)	Low (0)	Little_Weak (2)
Low (0)	High (2)	Medium (1)	Weak (1)
Low (0)	High (2)	High (2)	Very_Weak (0)
Medium (1)	Low (0)	Low (0)	Little_Strong (2)
Medium (1)	Low (0)	Medium (1)	Higher_Medium (5)
Medium (1)	Low (0)	High (2)	Medium (4)
Medium (1)	Medium (1)	Low (0)	Higher_Medium (5)
Medium (1)	Medium (1)	Medium (1)	Medium (4)
Medium (1)	Medium (1)	High (2)	Lower_Medium (3)
Medium (1)	High (2)	Low (0)	Medium (4)
Medium (1)	High (2)	Medium (1)	Lower_Medium (3)
Medium (1)	High (2)	High (2)	Little_Weak (2)
High (2)	Low (0)	Low (0)	Very_Strong (8)
High (2)	Low (0)	Medium (1)	Strong (7)
High (2)	Low (0)	High (2)	Little_Strong (6)
High (2)	Medium (1)	Low (0)	Strong (7)
High (2)	Medium (1)	Medium (1)	Little_Strong (6)
High (2)	Medium (1)	High (2)	Higher_Medium (5)
High (2)	High (2)	Low (0)	Little_Strong (6)
High (2)	High (2)	Medium (1)	Higher_Medium (5)
High (2)	High (2)	High (2)	Medium (4)

Numbers of 27 rules are applied to the fuzzified inputs. In fuzzy logic systems, in order to control the output variable, rule base is constructed. A fuzzy rule is a simple IF-THEN rule with a condition and a conclusion [17]. Fuzzy rules of our system are given in Table1. 0, 1 and 2 values are set for

the each degree of input parameters, namely, low, medium and high, respectively. The values for the degrees of compressive output parameter are calculated with the following formula:

$$\text{Compressive} = 2 \times \text{hidrate} + (2 - \text{unhidrate}) + (2 - \text{pore}) \quad (\text{Eq.1})$$

According to this formula, while the increase in the values of unhidrate and pore parameters has negative effect on compressive, increase in the value of hidrate has possitive effect. Fuzzy rules are set up in relation to this logic.

In inference phase of the proposed system, the result of each rule is evaluated and all results are combined in order to obtain a fuzzy output. Mamdani method [16] is used for fuzzy inference technique. The output obtained from the inference step is a fuzzy value, hence in defuzzification step, this output is defuzzified to obtain a final crisp output according to the membership function of the output variable [17-19]. There are many different types of defuzzification techniques in literature. In this study, center of gravity (COG) defuzzification technique in which the centroid of the composite area is calculated as a final crisp output is preferred to use.

### 4. Simulation Results of the Proposed Fuzzy Logic System

The proposed fuzzy logic model is implemented with MATLAB tool. Fig 5. shows an example operation of our system for the input parameters of values: Hidrate: 40 Pore: 13 and Unhidrate: 27.5. These values of hidrate, pore and unhidrate correspond to medium, medium and medium fuzzy degrees respectively. According to the fuzzy rule "If (Hidrate is Medium) and (Pore is Medium) and (Uc is Medium) then (Compressive is Medium)", the proposed system inferences that, these input values correspond to the value of 12 for the compressive crisp output. The Surface Screen Interface of the Proposed Fuzzy Logic Model is shown in Figure 6.

The measured compressive strength values of cement

mortar specimens were also correlated with the predicted values by established fuzzy logic model. The relationship

between measured and predicted strength values is plotted in Figure 7.

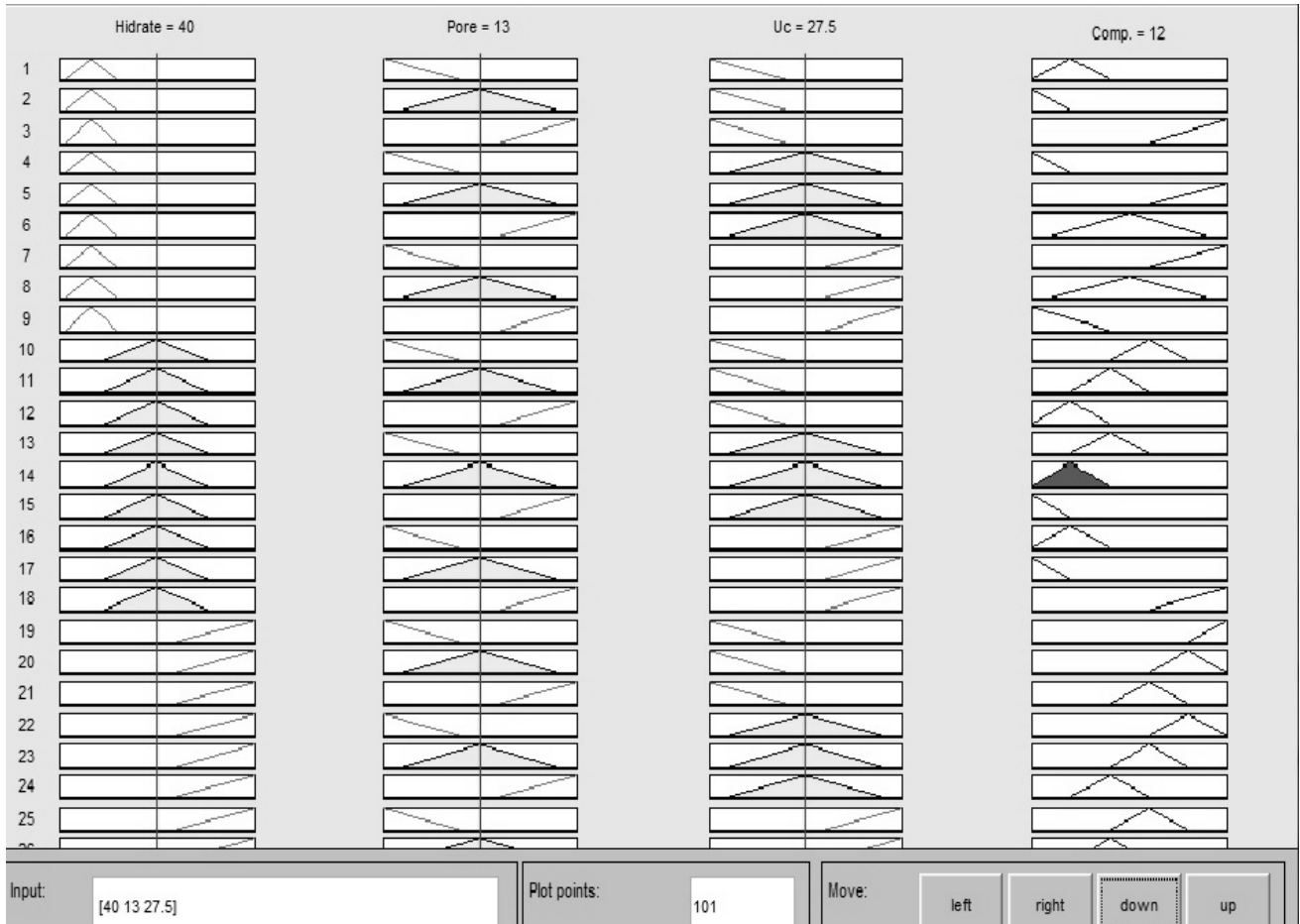


Figure 5. Interface of the proposed Fuzzy Logic System

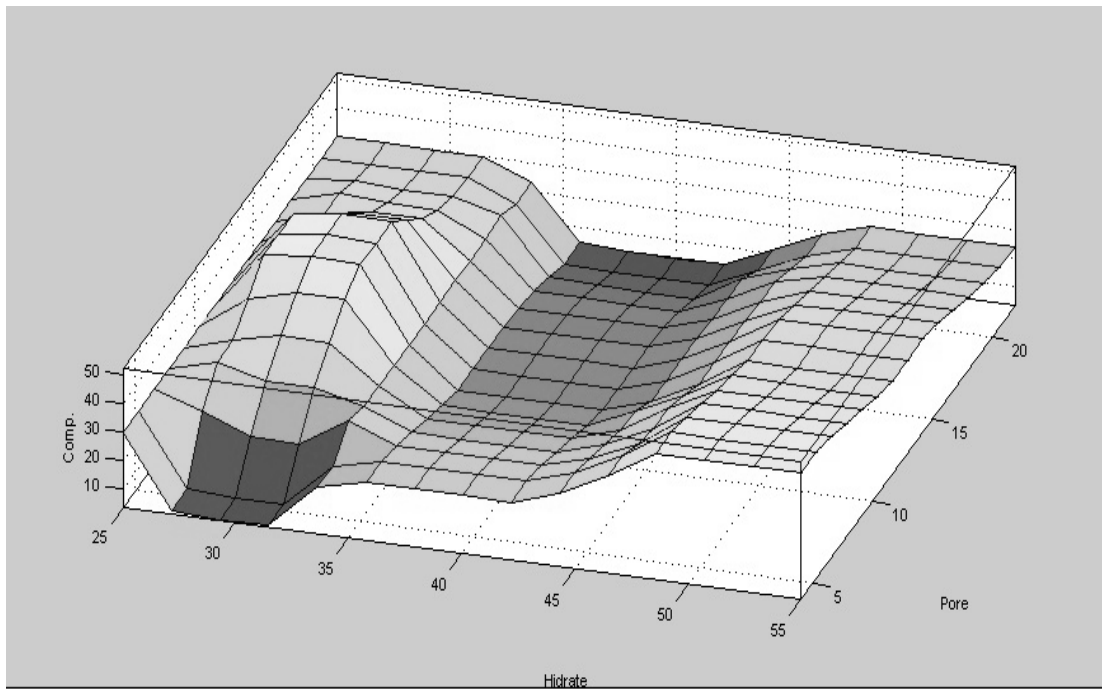


Figure 6. The Surface Screen Interface of the Proposed Fuzzy Logic Model

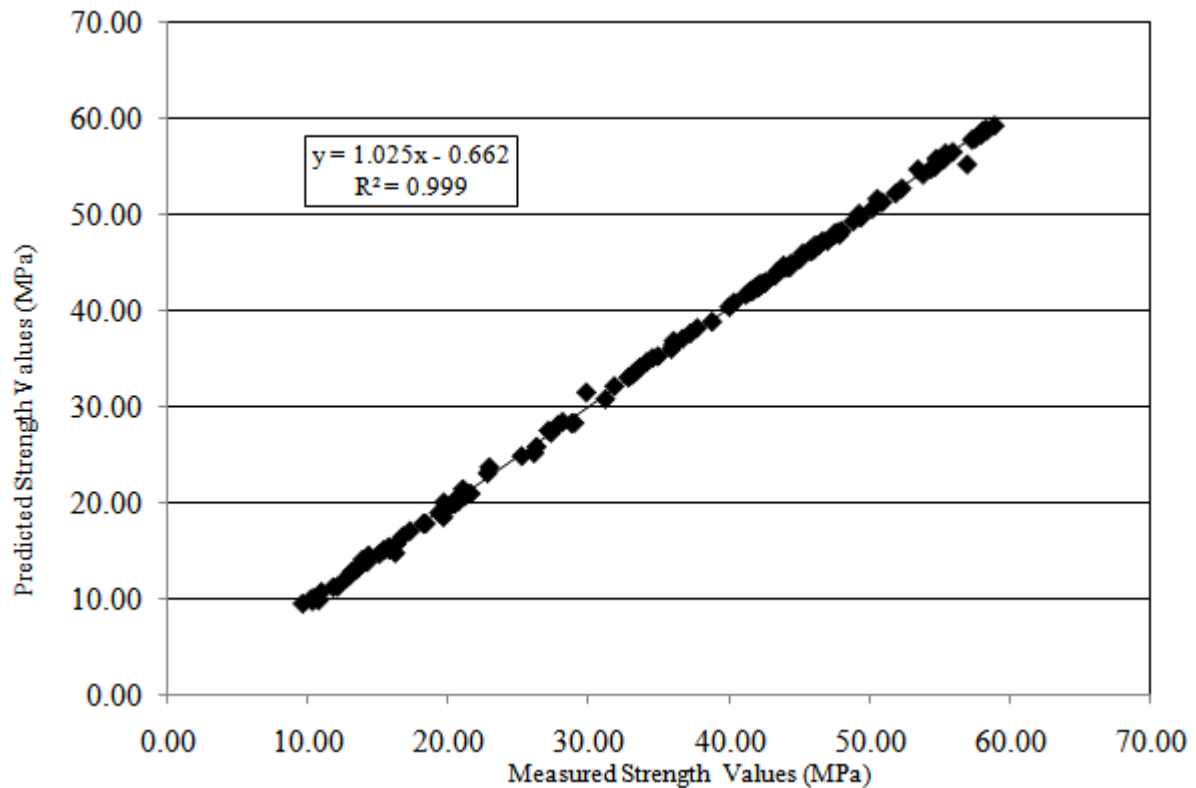


Figure 7. The relationship between measured and predicted strength values

## 5. Conclusions

In recent years, different optimization techniques have been commonly used in many various engineering problems. In this study, a fuzzy logic prediction model is proposed for calculating the compressive strength of cement mortars with the input parameters of pore area, unhydrated part and hydrated part of cement mortars. In this study, a relationship between the microstructure formation and compressive strength of cement mortars is established by fuzzy logic model. All data have been obtained from compressive strength test and from microstructural analysis of polished sections of cement mortars which have been examined under this strength test. All data can be obtained with these two experimental analyses. They are available to obtain in all modern laboratories. The fuzzy logic model aims to predict such strength values by using only microanalysis without using destructive test methods such as compressive strength test. Predicted results with fuzzy logic system are compared with the measured results and it has been found remarkably close to each other. There is a good correlation between measured and predicted values ( $R^2=0,9993$ ). These results show that the fuzzy logic technique can be used significantly to predict compressive strength of the cement mortars.

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