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ORIGINAL ARTICLE

Prediction of the effects of fly ash and silica fume on the setting time of Portland cement with fuzzy logic

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Abstract Fuzzy logic has recently been widely used to model in many areas of civil engineering applications. Especially as a result of the findings of experimental studies with fuzzy logic to predict good results have been obtained. In this study, Portland cement is composed of fly ash and silica fume with determined proportional. By this procedure, eight different mixtures were prepared and the effect of cement was investigated on the starting and finishing time of the setting. According to the results obtained in the setting time and finishing, all the mixing ratio of the prolonged period of time was determined. Also, by using fuzzy logic method, prediction model was formed based on the quantity of fly ash and silica fume to predict the initial and final setting times of cement, which could not be determined with experimental approaches. The experimental results are compared with the fuzzy logic results, and the correlation coefficients for the initial and final setting time are found 0.96 and 0.92, respectively. These results show that the developed model can be successfully applied in the cement industry.

Keywords Fuzzy logic · Cement · Setting time · Silica fume · Fly ash

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1 Introduction

Cement and pozzolanas are the fundamental building materials, which are widely used in construction industry. Pozzolanic materials are widely used in the production of concrete since they facilitate waste recycle for ecological balance [1] and due to financial reasons [2]. Furthermore, pozzolanic materials are indispensable components in cement and concrete fields owing to their advantages such as resistance and endurance [3–5], being light [6], permeability reduction [7], control of alkaline aggregate development [8], providing chemical resistance [9], and concrete retreat reduction[10].

In addition to these advantages, pozzolanic materials are also effective on setting time. Setting of the cement can be defined as the hardening of the cement upon its reaction with water. When this process occurs, rapidly some problems may arise during the transportation and placement of the fresh concrete. On the other hand, when hardening takes longer, then concrete may not acquire the resistance in desired time and molding time may be delayed. For this reason, standards specify the initial setting time as at least 1 h and final setting time as 10 h [11, 12]. For this purpose, chemical or mineral materials having different characteristics are added to cement in different amounts in order to increase or decrease setting time according to desired properties. Celik et al. [13] studied the effect of silica fume (SF) on setting time. According to the obtained results, it is found that a substitution ratio of 5 % does not have an effect on setting time, whereas 15 % significantly delays setting time. Simsek et al. [14] found that SF-substituted cements with 15 % substitution ratio delay initial and final setting times 90 and 150 min, respectively. Celik et al. [15] found that 5, 10, 15, and 20 % substitution of fly ash (FA) delays setting time for all ratios. Dorum and Tekin [16]

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found in their research that FA substitution delays the setting time by 5, 10, 15, and 20 % for both city water supply and distilled water.

Recent experimental works have been modeled with fuzzy logic, and the obtained results reached satisfactory levels. Fuzzy logic is one of the methods, which give the computers the ability to make a decision. In fuzzy logic, crisp input values are fuzzified between 0 and 1. Decision-making criteria of the computer are defined by forming rule table. At the output unit, fuzzy output values are defuzzified [17]. Fuzzy logic is now used in various fields of construction. Ozgan and Yildiz [18] substituted chrome magnesite brick dust into cement in 5, 10, 15, 20, and 25 % ratios and found that 5 % substitution shortens the initial setting time, whereas others delay it. Moreover, they tried to estimate these values by using fuzzy logic and as a result, they proposed that fuzzy logic can be used in estimating cement's initial and finish setting time in relation to the chrome magnesite brick dust amount. In addition to these, modeling studies of pressure resistance estimation of cement with various pozzolanic material substitutions were made with artificial neural networks and fuzzy logic and the obtained values were very close to experimental results [19–24]. Subasi et al. [25] used the fuzzy logic model for predicting compressive strength of concretes containing silica fume (0, 5, and 10 %). Their results show that fuzzy logic systems used for the prediction of 7, 28, and 90 days compressive strength using ultrasonic pulse velocity, Schmidt hardness, and percentage of silica fume as inputs. Nazari [26] investigated that prediction of water absorption of lightweight geopolymers produced by fine fly ash and rice husk–bark ash together with palm oil clinker aggregates by using adaptive network-based fuzzy inference systems. Subasi et al. [27] reported that an adaptive neuro-fuzzy inference system (ANFIS) presented for the prediction of early heat of hydration of plain and blended cements. Their study used five input parameters such as the additives percentage, grinding type and finesses of cements, and an output parameter that is heat of hydration of cements. Their results can be used in the prediction of early heat of hydration of plain and blended cements with ANFIS.

The initial and final setting times depend on many factors such as chemical components and temperature. Different rations of FA and SF are used in this study, and the other parameters and chemical components are ignored. Many experimental studies must be carried out to determine the effects of setting times of SF and FA ratios. Developing the model will decrease financial cost and trial time. In this work, the effects of the cements formed by substituting Portland cement (PC) with different ratios of FA and SF on initial and final setting times are studied. The obtained results are compared with reference values, and it is aimed to estimate cement's initial and final setting times with fuzzy logic method.

2 Material and method

2.1 Material

In this study, CEM I 42.5 R Portland cement produced my Bursa Cement Factory is used as reference. FA (Kutahya Seyitomer Thermal Plant) and SF (Antalya Etibank Electoferrochrome Facility) are used as pozzolanic material. In the preparation of cement paste, city water supply of Bursa Province Kestel District is used. Analysis results depicting the chemical compositions of the materials used are given in Table 1.

2.2 Method

In this study, eight different mixtures are done where PC is reference. The produced reference and blended cement codes are given in Table 2.

Table 1 Chemical compositions of tested materials

Materials	PC (%)	FA (%)	SF (%)
Chemical composition (%)			
SiO_2	21.82	53.39	78.50
Al_2O_3	6.49	16.07	1.22
Fe_2O_3	1.93	13.05	1.27
CaO	60.74	6.33	1.27
MgO	1.08	5.48	5.32
SO_3	2.62	1.06	0.15
Na_2O	0.14	1.59	1.78
K_2O	0.65	1.71	4.11

Table 2 Codes of reference and blended cements

Number of samples	Cement type	Cement code
1	Portland cement (PC 42.5 R)	M1
2	FA-substituted cement, 10 %	M2
3	FA-substituted cement, 20 %	M3
4	FA-substituted cement, 30 %	M4
5	SF-substituted cement, 5 %	M5
6	SF-substituted cement, 10 %	M6
7	FA- and SF-substituted cement, 5 + 5 %	M7
8	FA- and SF-substituted cement, 10 + 10 %	M8

Initial and final setting times of each cement are determined with 3 experiments in accordance with TS EN 196-3 [28]. Initial and final setting times are performed in Bursa Cement Factory by using Atom Technik brand Vicat ring, probe, and needle. This process is undertaken in a laboratory environment where ambient temperature is 20 °C and relative humidity is 65 %. With the help of Vicat apparatus, initial and final setting times are determined as follows; the time needed for the Vicat needle to sink into cement paste until there is 4 mm distance between the needle and the glass board is said to be initial setting time, whereas the time needed for the needle to sink into cement paste until there is 0.05 mm distance between the needle and the top of cement paste is taken as final setting time.

3 Prediction of the setting time with fuzzy logic

The percentage ratios of FA and SF's weights are used as inputs for fuzzy logic system. In fuzzification of these input values, fuzzy sets given in Fig. 1 are used. FA and SF percentage ratios are split into five input sets for fuzzification. The shape and values of fuzzy sets are taken from experimental results. In relation to these, crisp input data are fuzzified. Since triangular membership functions are used in the calculation of membership degrees, the following relation is used [17]:

$$\mu(x) = \begin{cases} 0 & \text{for} \quad x < a \\ \dfrac{x-a}{b-a} & \text{for} \quad a < x < b \\ \dfrac{c-x}{c-b} & \text{for} \quad b < x < c \\ 0 & \text{for} \quad c > 0 \end{cases} \tag{1}$$

here a, b, and c indexes show the crisp values of triangular membership functions. For example when FA ratio is 25 % and membership degrees of A1, A2, and A5 sets are 0, membership degrees of sets A3 and A4 can be calculated as 0.3 and 0.7, respectively. If the FA ratio is 35 % or above, when the membership degree of set A5 is 1, the membership degrees of other sets will be 0. Equation 1 is also used in calculation and fuzzification of membership degrees of Silica fume. For example when SF ratio is 2 % and membership degrees of sets B1 and B2 are 0.33 and 0.67, respectively, then membership degrees of other sets will be 0.

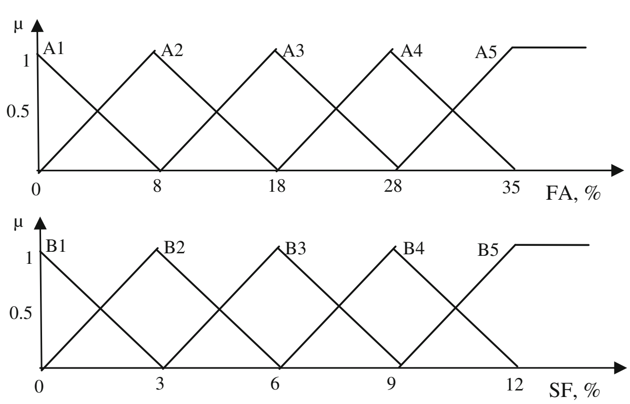

Fig. 1 Membership functions of input variables

For membership functions of the output variables, that is, initial and final setting times, triangle and trapezoid shapes are preferred as seen in Fig. 2. In determining the shape of output membership functions, again, experimental results are taken into account.

The main structure of fuzzy decision-making systems is the rule bases. Computer takes these rule bases into account in order to make a decision. Experts are consulted while forming these matrices. By taking previous professional experiences and experimental results into account, rule matrices in Tables 3 and 4 are formed for initial and final setting times, respectively [29].

Since input variables are identical for both initial and final setting times, the rule bases are merged and a total of 25 "If–then" relations are obtained as sampled below.

If input1 = A1 and input2 = B1, then output1 = O1 and output2 = C1
If input1 = A4 and input2 = B3, then output1 = O4 and output2 = C4

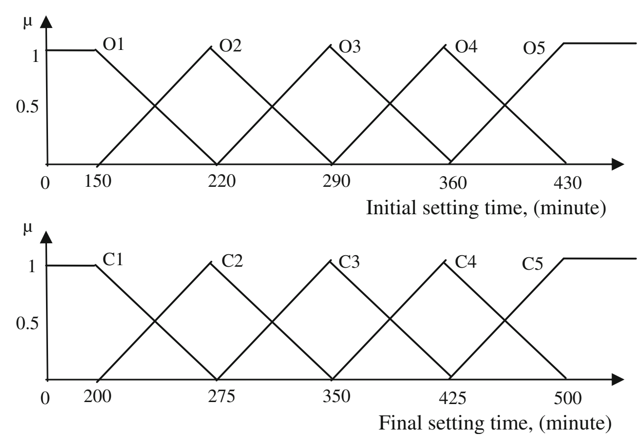

Fig. 2 Membership functions of output variables

Table 3 Rule base of initial setting time

	A1	A2	A3	A4	A5
B1	O1	O1	O2	O3	O3
B2	O2	O2	O2	O3	O3
B3	O2	O3	O3	O4	O4
B4	O4	O4	O5	O5	O5
B5	O4	O5	O5	O5	O5

Table 4 Rule base of final setting time

	A1	A2	A3	A4	A5
B1	C1	C1	C3	C4	C4
B2	C1	C2	C3	C4	C4
B3	C3	C3	C4	C4	C5
B4	C4	C4	C5	C5	C5
B5	C4	C5	C5	C5	C5

If input1 = A5 and input2 = B4, then output1 = O5 and output2 = C5

When the inputs of "If–then" relations are taken into consideration, it can be observed that they are linked with the conjunction "*and.*" In appointing membership degrees to output sets in a logical relation, the conjunction "*and*" appoints the minimum of input membership degrees. As a result of this logical relation, *max–min* inference method is used in fuzzy inference. For defuzzification which is the last phase of fuzzification operation, *weighted average* method is selected. This method is given by the equation below

$$x^* = \frac{\sum_{i=1}^{n} \mu_i(x).x_i}{\sum_{i=1}^{n} \mu_i(x)} \quad (2)$$

where x^* the defuzzification output value, μ_i the membership degree of each rule's output, and x_i the weighted average of each rule [29, 30]. Finally, the flow chart of the programming is prepared in accordance with the above information. A flow chart of the algorithm is shown in the Fig. 3.

4 Findings

Tables 5 and 6 show the initial and final setting times, respectively, according to the results obtained from the experiments performed in compliance with TS EN 196-3 on cement pastes used in this study and the results obtained from fuzzy logic model.

According to Table 5 with FA and SF addition to PC, the initial setting time of the cement paste, when compared to reference value, is extended for all mixture ratios. In FA-substituted cement, initial setting time is extended, in direct proportion with admixture ratio, by 26 % in M2 grade cement, 49 % in M3 grade cement, and 88 % in M4 grade cement. In SF-substituted cement, initial setting time is extended by 54 % in M5 grade cement, whereas M6 grade cement has a significant effect, which extends the initial setting time by 134 %. In cements with both FA and SF substitution, initial setting time is extended by 57 % in M7 grade cement and 171 % in M8 grade cement due to the

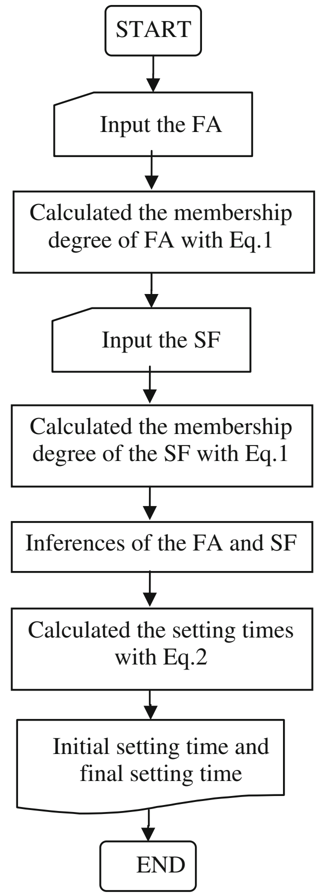

Fig. 3 A flow chart of the fuzzy logic algorithm

fact that both of the pozzolanic additives extend the setting time. When a general assessment is made, the minimum extension with respect to reference cement M1 is found to be 26 % in M2 grade cement paste, while the maximum extension is found as 171 % in M8 grade cement paste and a linear increase for all mixture ratios is observed. When these times are examined, it can be observed that minimum setting time is provided to be more than 60 min.

According to Table 6 with FA and SF addition to PC, the final setting time of the cement paste, when compared to reference value, is extended for all mixture ratios. In FA-substituted cement, final setting time is extended, in direct proportion with admixture ratio, by 11 % in M2 grade cement, 67 % in M3 grade cement, and 93 % in M4 grade cement. In SF-substituted cement, final setting time is extended by 41 % in M5 grade cement, whereas M6 grade cement has a significant effect, which extends the final setting time by 206 %. In cements with both FA and SF substitution, final setting time is extended by 74 % in M7 grade cement and 138 % in M8 grade cement due to the fact that both of the pozzolanic additives extend the setting time. When a general assessment is made, the minimum extension with respect to reference cement M1 is found to

Table 5 Initial setting times of the cements (minute)

Number of samples	Cements							
	M1	M2	M3	M4	M5	M6	M7	M8
1	145	175	230	280	230	370	240	425
2	165	190	240	300	245	360	250	415
3	155	220	225	295	240	360	240	420
Average	155	195	232	292	238	363	243	420
Index (%)	100	126	149	188	154	234	157	271
Estimates with fuzzy logic, $R^2 = 0.96$	144	162	237	290	220	360	262	391

Table 6 Final setting times of the cements (minute)

Number of samples	Cements							
	M1	M2	M3	M4	M5	M6	M7	M8
1	190	210	325	340	265	420	345	490
2	210	230	345	420	290	415	360	480
3	210	240	350	415	305	420	355	480
Average	203	227	340	392	287	418	353	483
Index (%)	100	111	167	193	141	206	174	238
Estimates with fuzzy logic, $R^2 = 0.92$	195	237	368	425	297	425	295	469

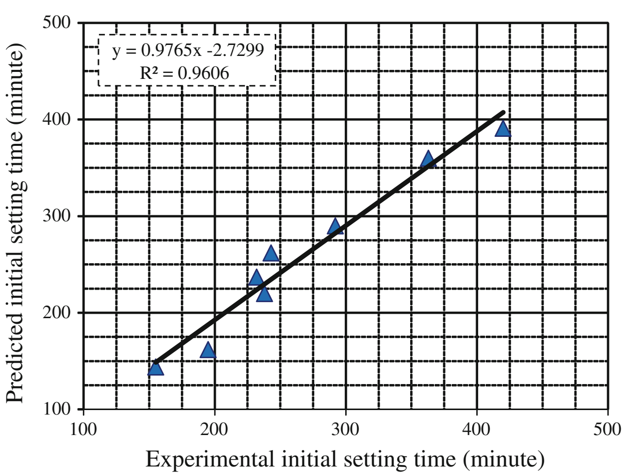

Fig. 4 Relationship between experimental and predicted values for initial setting times

be 12 % in M2 grade cement paste, while the maximum extension is found as 138 % in M8 grade cement paste and a linear increase for all mixture ratios is observed. When these times are examined, it can be observed that maximum setting time is provided to be less than 600 min.

In general, when average initial setting times are compared, the reference M1 cement has the minimum time that is 155 min and M8 grade cement has the maximum time (Table 5). It is observed that the same situation appears for final setting times (Table 6).

Initial setting times which are experimentally obtained and estimated with fuzzy logic are given in Fig. 4, whereas final setting times are given in Fig. 5.

When the results obtained from performed experiments and the estimations made by the fuzzy logic and correlation coefficient are taken into account, it is observed that very close results are obtained for initial setting time ($R^2 = 0.96$) and final setting time ($R^2 = 0.92$) (Figs. 4, 5).

5 Results and recommendations

5.1 Results

In this study, the effects of reference FA- and SF-substituted cements on the initial and final setting times are studied, estimation models are formed with fuzzy logic method for estimating initial and final setting times in accordance with FA and SF amount, and experimental results and estimated values are compared and evaluated.

- As a result of experiments, minimum initial setting time is found to be 145 min for reference samples M1 while average initial setting time is 155 min. On the other hand, average final setting time is determined as 227 min.
- When FA is substituted into PC in 10 % ratio, M2 initial and final setting times are measured on average as 195 min and 227 min, respectively. On the other

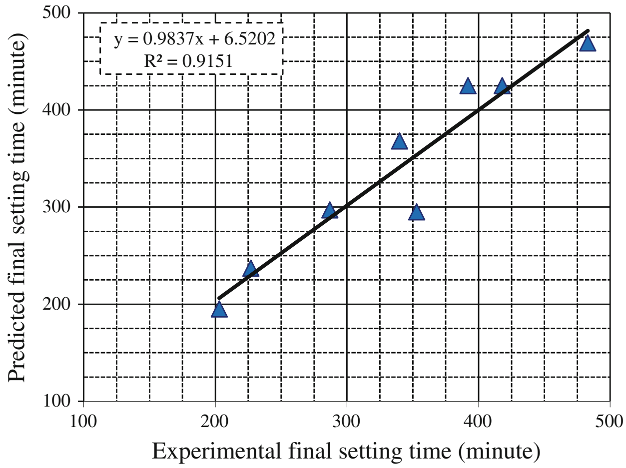

Fig. 5 Relationship between experimental and predicted values for final setting times

hand, it is determined that average initial setting time is 26 % more than the reference value while final setting time is 11 % longer.

- When FA is substituted into PC in 10 % ratio, M2 initial and final setting times are measured on average as 195 min and 227 min, respectively. On the other hand, it is determined that average initial setting time is 26 % more than the reference value while final setting time is 11 % longer.
- When FA is substituted into PC in 20 % ratio, M3 initial and final setting times are measured on average as 232 and 340 min, respectively. On the other hand, it is determined that average initial setting time is 49 % more than the reference value while final setting time is 67 % longer.
- When FA is substituted into PC in 30 % ratio, M4 initial and final setting times are measured on average as 292 and 392 min, respectively. On the other hand, it is determined that average initial setting time is 88 % more than the reference value while final setting time is 93 % longer.
- When FA is substituted into PC in 5 % ratio, M5 initial and final setting times are measured on average as 238 and 287 min, respectively. On the other hand, it is determined that average initial setting time is 54 % more than the reference value while final setting time is 41 % longer.
- When SF is substituted into PC in 10 % ratio, M6 initial and final setting times are measured on average as 263 and 418 min, respectively. On the other hand, it is determined that average initial setting time is 134 % more than the reference value while final setting time is 106 % longer.
- When FA (5 %) and SF (5 %) are substituted into PC, M7 initial and final setting times are measured on average as 243 and 353 min, respectively. On the other hand, it is determined that average initial setting time is 57 % more than the reference value while final setting time is 74 % longer.
- When FA (10 %) and SF (10 %) are substituted into PC, M8 initial and final setting times are measured on average as 429 and 483 min, respectively. On the other hand, it is determined that average initial setting time is 171 % more than the reference value while final setting time is 138 % longer.
- The model formed with fuzzy logic yielded initial setting time values similar to the ones obtained from experiments. The correlation coefficient between the estimated and experimental values is found as 0.96. Likewise, it is determined that the estimated and experimental values for final setting time are very similar and the correlation coefficient between them is 0.92. When the results are examined, it is understood that fuzzy logic method can be used in estimating initial and final setting times of cement depending on FA and SF amounts.

5.2 Recommendations

Nowadays, set delaying or accelerating admixtures are widely used with cement. However, in this study, the feasibility of using FA and SF, which have an important place among mineral materials for environment pollution and ecological balance protection, as set delaying or accelerating agents in cement is studied. Using the obtained experimental results, estimation models are formed with fuzzy logic for setting times and it is observed that these models can be used for estimating setting times of FA and SF. For this reason, it is thought that these pozzolanas can be used with chemical additives or instead of chemical additives in cement as set delaying or accelerating agents. However, it will be beneficial to conduct experiments on cements obtained with the substitution of these materials in order to assess physical characteristics such as pressure resistance, expansion values, void ratio, unit volume weights, and water absorption ratios. Furthermore, it is anticipated that some of these experiments, pressure resistance being the first, can be modeled with fuzzy logic.

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