Evaluating the potential of fuzzy logic to predict compressive strength of lightweight concrete, SCC, and fly ash

Milad Ghanbari, Mohammad Hossein Fardani and Majid Ghanbari

Evaluating the combined impact of fly ash (FA), lightweight concrete, and self-compacting concrete (SCC) to predict compressive strength, considering its increasing application in concrete structures, is a novelty. In general, concrete is a mix of a lot of material, and predicting the optimal compressive strength of lightweight concrete, SCC, and FA is a hard task. However, it seems that a soft computing could do this economizing on time and cost. In this paper, four different models were separately designed by means of fuzzy logic (FL) in a numerical computing software to predict compressive strength of concrete under the above mentioned conditions. The paper aimed to evaluate the potential of fuzzy logic as a soft computing method. The results gained by FL were compared with those of the experimental methods. They were considerably close to each other which mean that fuzzy logic could be strongly applied to predict compressive strength of lightweight concrete, SCC, and FA.

1. INTRODUCTION

Despite hard computing which attempted to achieve precision and perfect modelling of facts, soft methods are based on tolerating imprecision, incomplete and unimportant details, and uncertainty. The better we understand the cause, the methodology, and the philosophy of such computing, the brighter the new horizons will be in complicated sciences in the future. In simple terms, hard methods are related with the nature and behavior of machine while soft methods are based on human and the decisions made by his mind to solve problems.

Now, at the age of creative technology, fuzzy logic (FL) is a mathematical application in addition to classic Boolean logic which has taken fast steps. Fuzzy logic is basically used to show uncertainty and ambiguity based on mathematics and it provides study tools with imprecision [1-3]. Utilizing the soft computing methods in ready mixed concrete plants is an attractive work [4-7].

Clearly, concrete is a mix of aggregate (gravel and sand or recycled aggregate), binder (cement and fly ash), water, and additives [4]. Using the recycled aggregates in concrete production helps countries in reducing greenhouse gases emissions specially Carbon dioxide [8-10]. Additives are used to improve the expected quality in the concrete. Fly ash is a pozzolan material which is extensively used as a substitute for cement to make high performance and high volume concrete. The advantage of such material in terms of durability of high strength concrete (HSC) is confirmed, and nowadays, the application of FA is common [11-13].

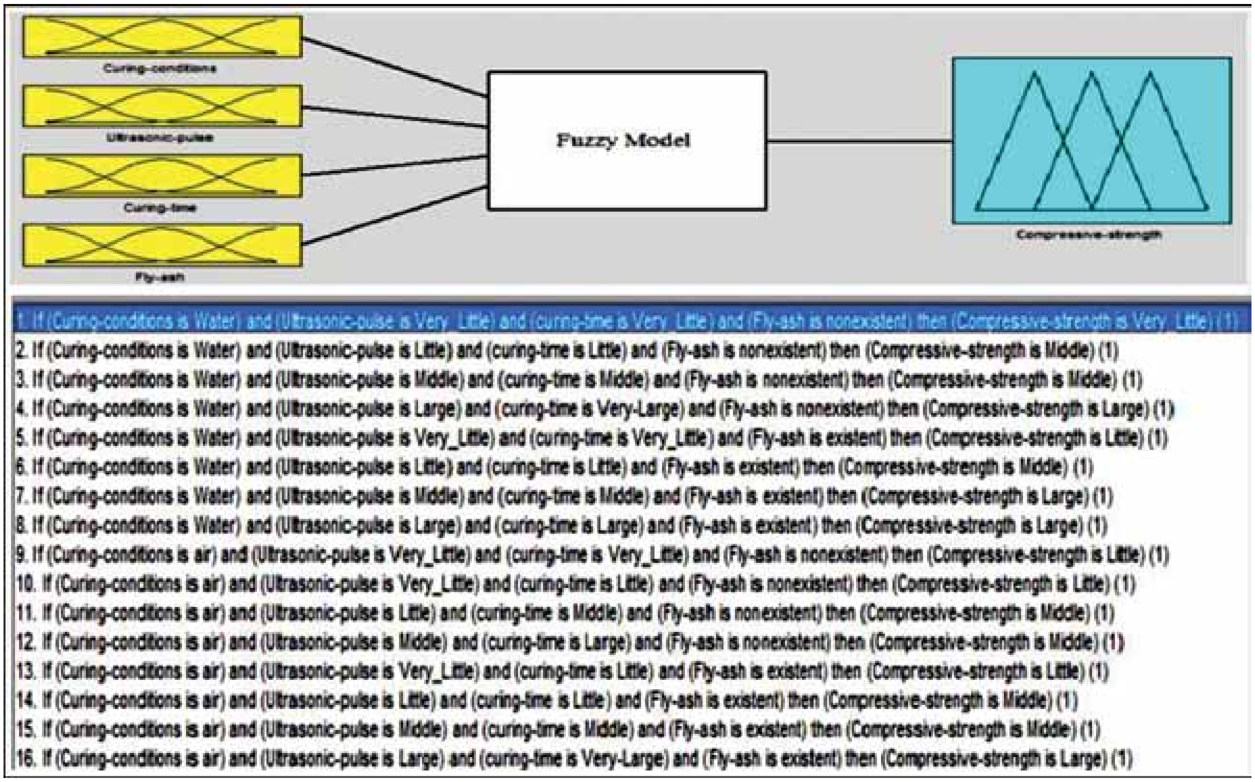
Generally, FA is smaller than Portland cement. According to the directive ASTM C 618, there are two extensive types of FA (C and F class) depending on the type of the burned coal. Fly ash type F ($CaO < 6\%$) is known as low calcium ash which is not a hardener by itself although it generally indicates pozzolanic features [14]. At early years, the compressive strength of the concrete with a high volume of FA is lower than the common concrete which is mainly due to a speed decrease in pozzolanic reaction of FA. An important feature required to use this material in construction is compressive strength [15]. Real compressive strength of concrete in the first years of a structure is unknown. The current experimental equations to calculate CS are based on the experiments of concrete without cement additives. One more thing to learn about the compressive strength of concrete is finding out more about the nature of concrete and methods to optimize concrete additives [16]. Additives such as FA and Silica Fume (SF) are used as a replacement for cement to improve mechanical properties (decrease in hydration and permeability) [1].

Due to the increasing importance of self-compacting concrete (SCC) and lightweight concretes and the ones with FA and other pozzolans, this paper aimed to evaluate fuzzy logic to predict the compressive strength of such concretes. Hence, the potential of fuzzy logic in four different modelling (Mamdani type) was evaluated in the numerical computing software. In each modelling, a separate database was used. The curing conditions of the concrete, age of the concrete, the type of additive, and the aggregate used were different in each model. This means that the input variables of each model were different, but the output variable was the same that is the compressive strength. It is known that ultrasonic test as a nondestructive method is used to measure compressive strength of concrete. Therefore, the velocity of Ultrasonic Pulse (UP) was considered as one of the inputs of lightweight concrete in the first model.

2. INFORMATION MODELLING

2.1. Model 1 (predicting compressive strength of lightweight concrete)

In this part, a fuzzy logic model was designed which predicted the compressive strength of lightweight concrete with slag aggregate and FA at the age of 3,7,14, and 28 days under different curing conditions. To do so, the databases of the study done by Qoskun and Tanyildizin were used [1]. They replaced 15 percent of the Portland cement with FA in the mixtures containing FA. The samples were kept in the curing condition with a temperature of 20±2° C. The compressive strength and



1. If (Curing-conditions is Water) and (Ultrasonic-pulse is Very_ Little) and (curing-time is Very_ Little) and (Fly-ash is nonexistent) then (Compressive-strength is Very_ Little) (1)
2. If (Curing-conditions is Water) and (Ultrasonic-pulse is Little) and (curing-time is Little) and (Fly-ash is nonexistent) then (Compressive-strength is Middle) (1)
3. If (Curing-conditions is Water) and (Ultrasonic-pulse is Middle) and (curing-time is Middle) and (Fly-ash is nonexistent) then (Compressive-strength is Middle) (1)
4. If (Curing-conditions is Water) and (Ultrasonic-pulse is Large) and (curing-time is Very-Large) and (Fly-ash is nonexistent) then (Compressive-strength is Large) (1)
5. If (Curing-conditions is Water) and (Ultrasonic-pulse is Very_Little) and (curing-time is Very_Little) and (Fly-ash is existent) then (Compressive-strength is Little) (1)
6. If (Curing-conditions is Water) and (Ultrasonic-pulse is Little) and (curing-time is Little) and (Fly-ash is existent) then (Compressive-strength is Middle) (1)
7. If (Curing-conditions is Water) and (Ultrasonic-pulse is Middle) and (curing-time is Middle) and (Fly-ash is existent) then (Compressive-strength is Large) (1)
8. If (Curing-conditions is Water) and (Ultrasonic-pulse is Large) and (curing-time is Large) and (Fly-ash is existent) then (Compressive-strength is Large) (1)
9. If (Curing-conditions is air) and (Ultrasonic-pulse is Very_Little) and (curing-time is Very_Little) and (Fly-ash is nonexistent) then (Compressive-strength is Little) (1)
10. If (Curing-conditions is air) and (Ultrasonic-pulse is Very_Little) and (curing-time is Little) and (Fly-ash is nonexistent) then (Compressive-strength is Little) (1)
11. If (Curing-conditions is air) and (Ultrasonic-pulse is Little) and (curing-time is Middle) and (Fly-ash is nonexistent) then (Compressive-strength is Middle) (1)
12. If (Curing-conditions is air) and (Ultrasonic-pulse is Middle) and (curing-time is Large) and (Fly-ash is nonexistent) then (Compressive-strength is Middle) (1)
13. If (Curing-conditions is air) and (Ultrasonic-pulse is Very_Little) and (curing-time is Little) and (Fly-ash is existent) then (Compressive-strength is Little) (1)
14. If (Curing-conditions is air) and (Ultrasonic-pulse is Little) and (curing-time is Little) and (Fly-ash is existent) then (Compressive-strength is Middle) (1)
15. If (Curing-conditions is air) and (Ultrasonic-pulse is Middle) and (curing-time is Middle) and (Fly-ash is existent) then (Compressive-strength is Middle) (1)
16. If (Curing-conditions is air) and (Ultrasonic-pulse is Large) and (curing-time is Very-Large) and (Fly-ash is existent) then (Compressive-strength is Large) (1)

Figure 1. The schematic of prediction model 1

the velocity of the UP were measured at the periods of 3,7,14, and 28 days.

This model includes four inputs and one output. The output is the compressive strength of concrete. The inputs include curing condition (water and air), velocity of UP, age of concrete, and volume of FA. Membership functions of the variables were triangular, and 16 fuzzy rules were set. The schematic sketch of the model can be observed in Figure 1.

2.2. Model 2 (predicting the compressive strength of SCC)

This model presents the prediction of compressive strength of SCC. The input of the model including 6 parameters namely the volume of cement, sand, coarse aggregate, and FA, the percentage of Superplasticizer, and water to binder ratio, and one output parameter, i.e. the compressive strength of 28 day old concrete were used for modelling. Membership functions of the input and output variables were triangular, and 60 fuzzy rules were defined (Figure 2). The success of this model

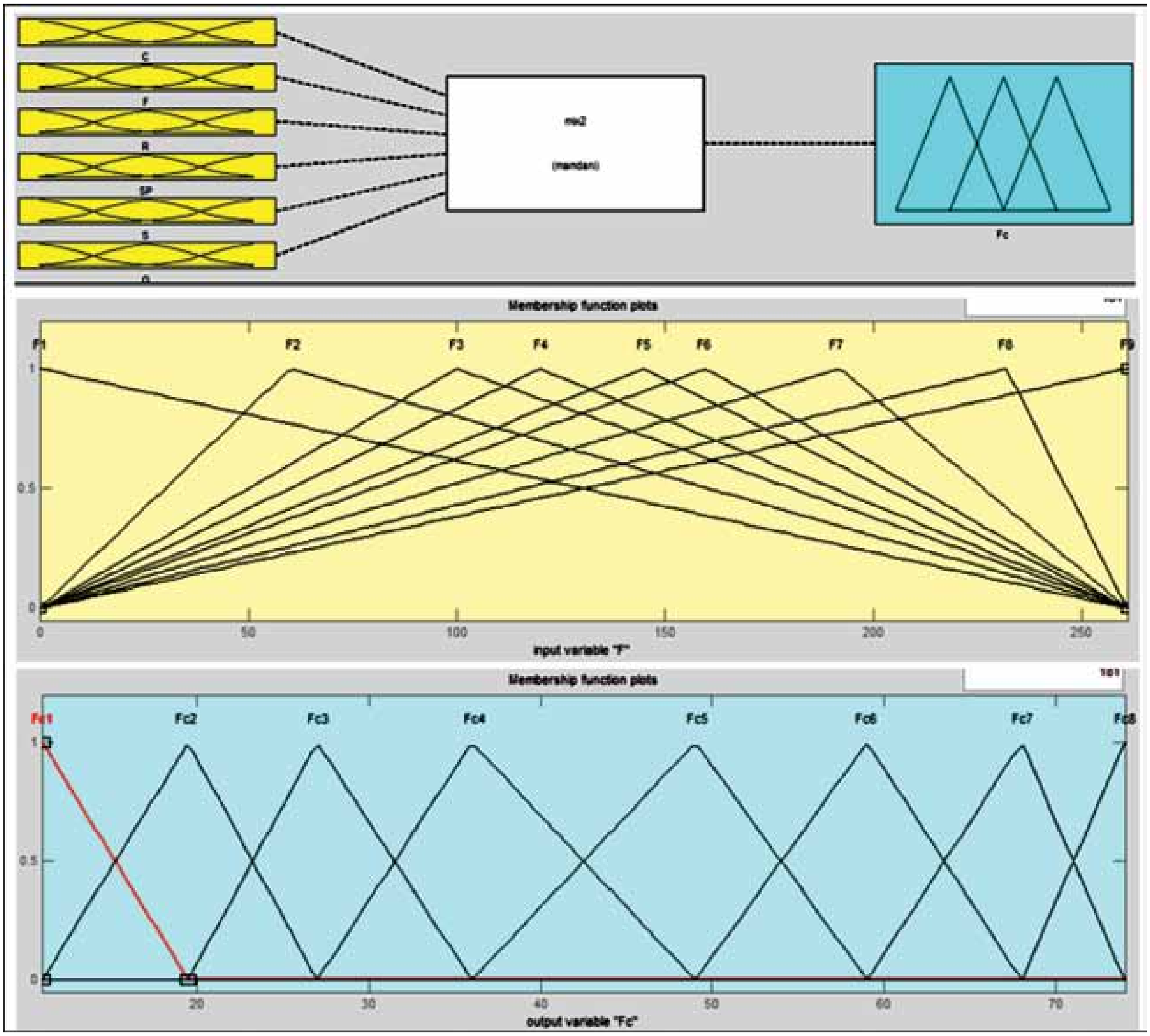


Figure 2. The schematic of prediction model 2

to predict the behavior of SCC mixtures depends on comprehensiveness of the training data. Therefore, the database of the study done by Aggarwal was used [2].

2.3. Model 3 (predicting the compressive strength of concrete containing FA)

In this part, the influence of fly ash on the compressive strength of concrete regarding the ratio of water/cement, and age of the concrete was studied by means of FL. To design the model, the database of the study by Uygunoğlu and Ünal was used [16]. In this concrete, FA was used with a ratio of 0%, 10%, 20%, and 30% to cement. The ratio of the water to the binder in these samples varied between 0.27 and 0.60 with six different numbers. In the modelling, the three inputs of R (ratio of water to binder), F (FA percentage), and Y (age of the sample), and the output C (compressive strength) were defined. R, F, and Y included 6, 4 and 6 types respectively. C included 144 quantities. 144 fuzzy rules were also defined (Figure 3).

2.4. Model 4 (predicting the compressive strength of common concrete)

This model includes two inputs and one output. The first input is the ratio of water to cement, and the second is the ratio of aggregate to cement. The output is the compressive strength of concrete. According to the

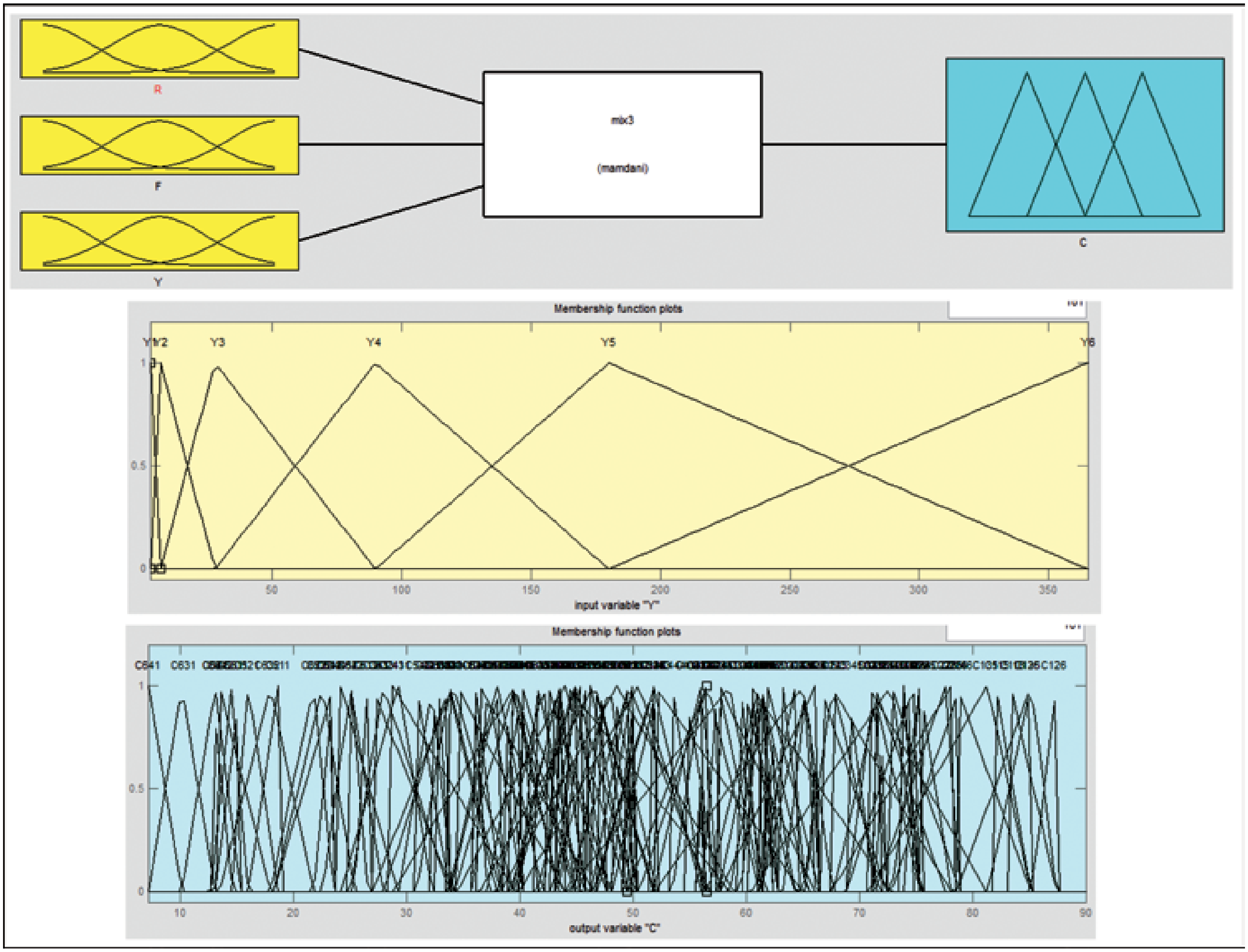
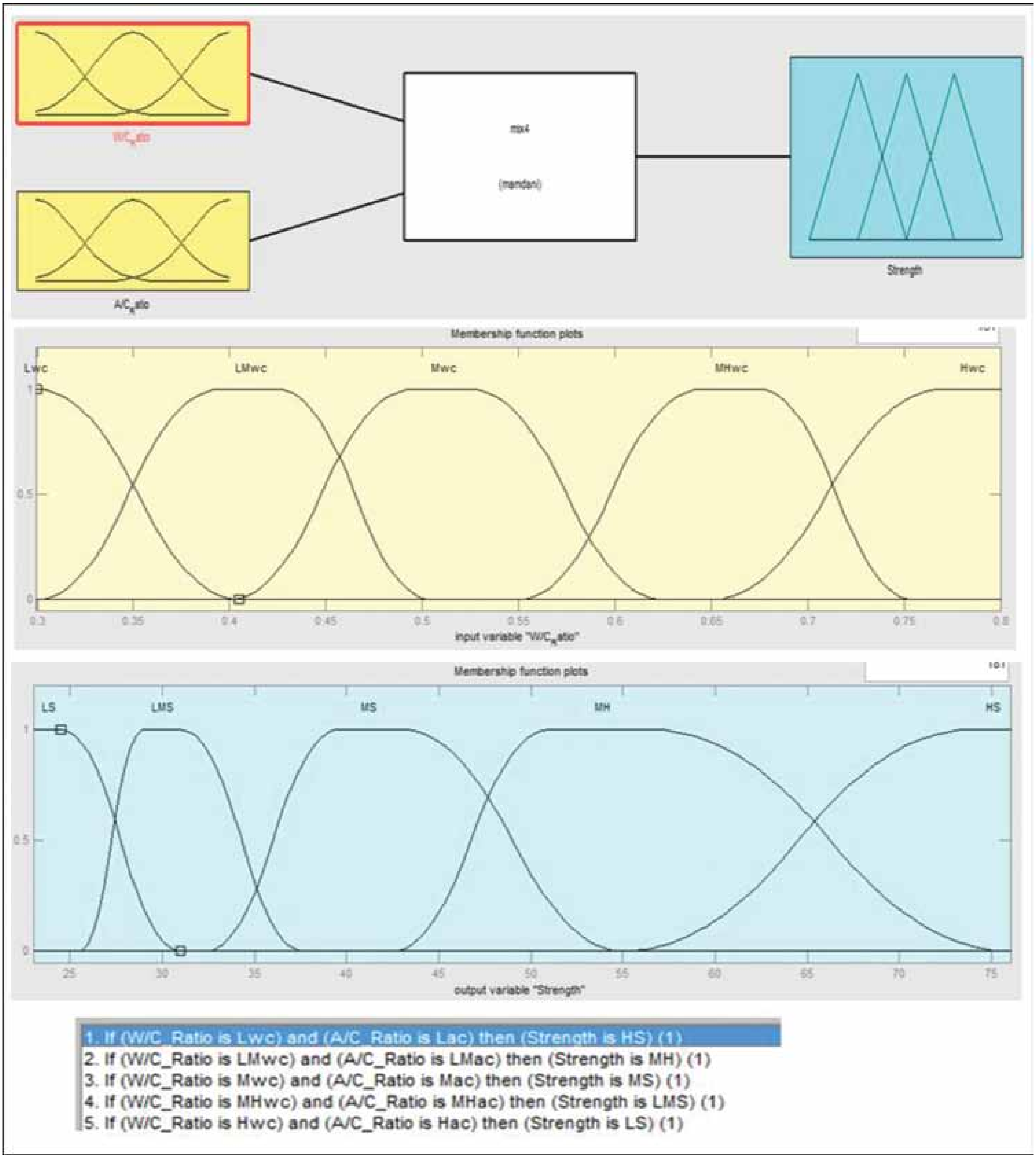


Figure 3. The schematic of prediction model 3



1. If (W/C_Ratio is Lwc) and (A/C_Ratio is Lac) then (Strength is HS) (1)
2. If (W/C_Ratio is LMwc) and (A/C_Ratio is LMac) then (Strength is MH) (1)
3. If (W/C_Ratio is Mwc) and (A/C_Ratio is Mac) then (Strength is MS) (1)
4. If (W/C_Ratio is MHwc) and (A/C_Ratio is MHac) then (Strength is LMS) (1)
5. If (W/C_Ratio is Hwc) and (A/C_Ratio is Hac) then (Strength is LS) (1)

Figure 4. The schematic of prediction model 4

relationship between the ratio of water to cement, and aggregate to cement, membership functions of these three variables were formed. Membership functions of the variables were defined as π-shaped and five fuzzy rules were used here (Figure 4). In this modelling, the database of the study by Nataraja et al was used [17].

Table 1. Comparison the experimental and predicted results in model 1

		3 days	7 days	14 days	28 days
Water Curing	Experimental results without FA	13.41	20.12	28.4	30.94
	Fuzzy logic results without FA	16.8	21.8	23.1	30.9
	Experimental results With Fly Ash	11.73	23.99	29.9	33.99
	Fuzzy logic results With Fly Ash	13.4	23.7	30.1	31
Air Curing	Experimental results without FA	12.32	14.73	20.14	24.87
	Fuzzy logic results without FA	12.5	17.1	23.1	23.5
	Experimental results With Fly Ash	9.09	18.2	22.35	27.32
	Fuzzy logic results With Fly Ash	12.5	20	23.1	30.8

Table 2. The absolute error of the predicted results in model 1

		3 days	7 days	14 days	28 days
Water Curing	without FA	20.17	7.70	22.94	0.12
	With FA	12.46	1.22	0.66	9.64
Air Curing	without FA	1.44	13.85	12.81	5.82
	With FA	27.28	9	3.24	11.29
Average Error %			9.982		

3. ANALYSIS

3.1. Model 1

The outputs of compressive strength by fuzzy logic model as well as error percentage of this model compared to the experimental results are included in Tables 1 and 2. As shown in the tables, the average of absolute error of the model was 10 percent which could be due to incomprehensiveness of the database to a large extent.

3.2. Model 2

Table 3 presents the results of the fuzzy model. The average of absolute error of the model is 6.2%. The

Table 3. Comparison the experimental and predicted results in model 2

No.	Experimental Strength (Mpa)	FL Strength (Mpa)	N.O	Experimental Strength (Mpa)	FL Strength (Mpa)	N.O	Experimental Strength (Mpa)	FL Strength (Mpa)
1	17	18.9	21	44	47.9	41	61.6	58.6
2	19.1	18.9	22	52	47.9	42	65.5	58.6
3	26.7	27.4	23	45	47.4	43	67.8	66.9
4	32.9	27.4	24	51	48	44	54.5	48.5
5	36.3	37.3	25	33	27.3	45	30.8	33.2
6	26.7	27.3	26	36	37.7	46	32.6	33.2
7	49	47.4	27	34.6	37.7	47	32.2	27.3
8	44	42.5	28	37.8	37.5	48	24	27.3
9	44	42.5	29	48.3	48	49	39.5	37.3
10	38	37.4	30	33.2	27.4	50	30.4	27.4
11	46	48.1	31	34.9	37.4	51	35.3	33.2
12	50	48	32	38.9	39	52	18.7	18.9
13	49	48	33	30.2	27.3	53	41.2	39.5
14	49	47.4	34	26.2	27.5	54	19.6	18.9
15	46	47.9	35	35.8	38.2	55	27.7	27.3
16	48	47.8	36	51.7	48	56	35	33.2
17	45	42.5	37	55.3	58.6	57	38.8	37.3
18	31	27.3	38	51.5	47.9	58	34.3	33.2
19	43	37.3	39	59.4	58.5	59	15.9	14.3
20	47	47.4	40	46.5	47.9	60	26.4	27.3

Table 4. Comparison the experimental and predicted results in model 3

W/b	FA %	Age of concretes (day)					
		3	7	28	90	180	365
0.27	0	54.1	59.8	70.7	74.4	83.2	85
	10	50.2	56.1	68.1	74.6	84	86.4
	20	42.7	49	61.5	69.5	79.1	83.7
	30	37.4	48.6	56	64.7	74.1	81
0.32	0	44.9	51.9	61.8	63.9	72.7	73.4
	10	43	50.4	60.9	64.9	76.4	76
	20	37.3	45	54.8	63.5	74.5	76.8
	30	32.6	39.9	48.9	60.2	70.9	75
0.35	0	43.1	49.4	56.1	61.3	68.4	72.7
	10	39.6	49.4	56.1	63	71.8	73
	20	33.5	44.7	54.3	61.7	70.9	74.9
	30	29.2	41	53	60.4	69.8	74.4
0.4	0	33	42.8	50.3	55.7	61.4	63.7
	10	31.9	41.2	49.7	56.9	62.5	66
	20	28.6	37.9	47	55.7	60.6	64.4
	30	25.9	35.4	44.3	54.1	58.7	62.8
0.55	0	17.5	26.2	36.7	41.9	47.6	48.3
	10	16.5	24.8	36.8	44.1	48.6	50.2
	20	14.4	22.1	34.3	42.9	48.9	50.9
	30	13.3	21.6	31.8	40.6	48.3	49.5
0.6	0	14.4	22.8	33.7	38.9	42.9	44.1
	10	12.9	21.1	32.1	39	44.3	46.5
	20	10.2	17.8	28.9	37.8	42.4	45.3
	30	7.95	14.9	26	36.3	40.5	43.8

correlation coefficient of the model compared to the experimental results was 0.95 which indicates a strong correlation (Figure 5).

3.3. Model 3

The results of the model, observed in Table 4, demonstrate that the average of absolute error of the model is 3.14%. This error is acceptable in engineering. Figure 6 shows the correlation diagram between the results of the compressive strength of the 28 day model and those of the experimental. As it can be observed, the correlation coefficient is 0.98 which is a strong one. The precision of this model could be due to the comprehensiveness of the database used, and the number of the fuzzy rules.

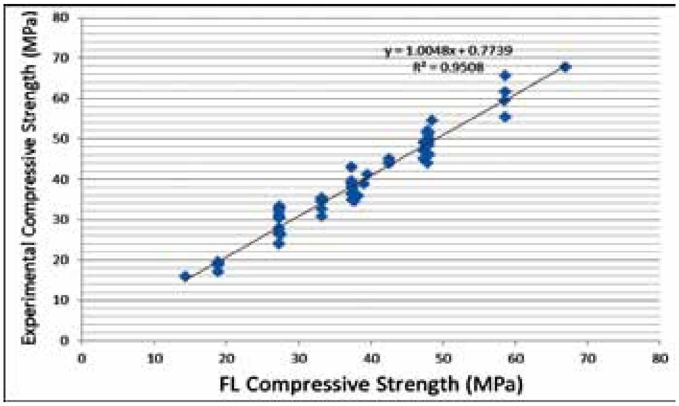


Figure 5. The correlation diagram of model 2

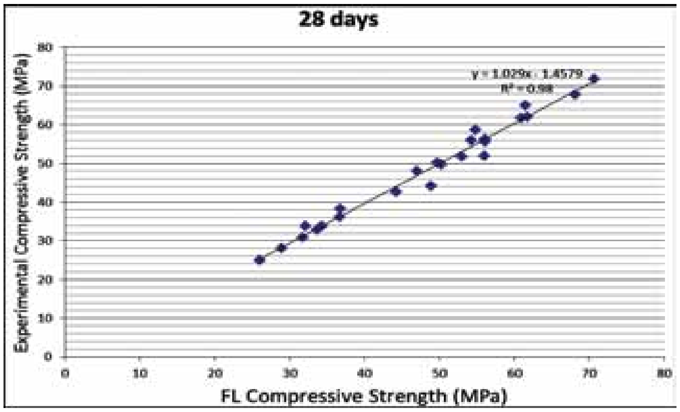


Figure 6. The correlation diagram of model 3

Table 5. Comparison the experimental and predicted results in model 4

w/c ratio	a/c ratio	Average strength experimental	Compressive strength of FL	Error
0.68	6.85	27.63	30.6	9.705
0.56	5.46	37.38	42.8	12.663
0.46	4.29	47.29	51.8	8.706
0.38	3.33	56.57	57.1	0.928
0.32	2.54	65.47	67.8	3.436
0.26	1.89	71.35	69.7	2.367
0.22	1.34	72.79	69.7	4.433
0.65	6.65	27.63	30.9	10.582
0.54	5.22	37.38	42.7	12.459
0.44	4.04	47.29	54.8	13.704
0.36	3.07	56.57	58.9	3.955
0.29	2.29	65.47	69.7	6.068
0.24	1.64	71.35	69.7	2.367
0.19	1.1	72.79	69.7	4.433
0.67	5.79	27.63	31.3	11.725
0.55	4.58	37.38	42.7	12.459
0.45	3.58	47.29	57.1	17.18
0.37	2.76	56.57	59.5	4.924
0.31	2.08	65.47	69.7	6.068
0.25	1.52	71.35	69.7	2.367
0.21	1.06	72.79	69.7	4.433
Mean error %		7.379		

3.4. Model 4

The results shown in Table 5 demonstrate that the average of absolute error in this model is 7.4%. Figure 7 shows the correlation diagram of the results of the fuzzy model and those of the experimental. The coefficient is 0.96.

4. CONCLUSION

Lightweight concrete is one of the certain kinds of concrete used in construction. The use of such concrete in sections with over designed reinforcing rebar requires high workability. Therefore, lightweight concrete has to be self-compacting. Since the volume of cement in self-compacting concrete (SCC) is more than the cement in the common concrete, there is certainly need for research in this area. SCC and fly ash (FA) concrete have a lot of significance in concrete technology which, due to their qualities, fresh or hardened, are extensively used in concrete structures. FA is a strong pozzolanic material which is a side product of thermal power plants. This material is used to improve durability and compressive strength of concrete, and it decreases concrete permeability against Chloride and Sulfide which eventually leads to more useful life of concrete.

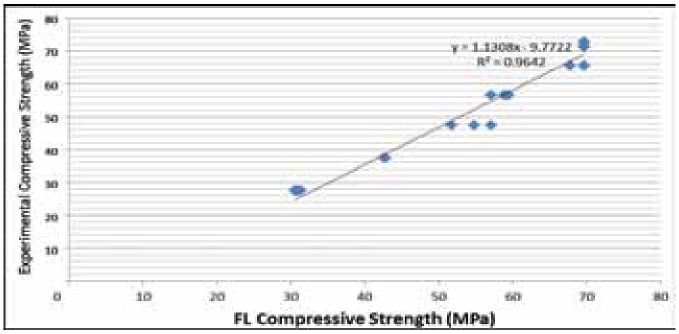


Figure 7. The correlation diagram of model 4

This study evaluated the potential of fuzzy logic (FL) to predict compressive strength of lightweight, SCC, FA and common concrete. To do so, four different fuzzy models with different inputs under different conditions were designed by means of the numerical computing software. In each of these models, the related experimental database was used.

The absolute error in the designed models was 3 to 10 percent. The results demonstrated that the difference between the experimental compressive strength of the concrete and that of the predicting model increased as the percentage of the substitute FA, and the ratio of water/binder increased. The models which enjoyed more fuzzy rules and more comprehensive databases showed lower error and stronger correlation coefficient. Therefore, FL could be a replacement to predict compressive strength of lightweight concrete, SCC, FA instead of destructive and semi-destructive methods.

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Milad Ghanbari holds a PhD in Construction Engineering and Management (CE&M) from Science and Research Branch from Islamic Azad University, Tehran, Iran. He is also a lecturer of CE&M at Islamic Azad University. For the last six years, he has been working in construction projects in Tehran. His research interests include construction project management, innovation in concrete production technology, sustainable development, recycling construction materials, system dynamics, C&D waste management, soft computing and optimization methods. He has published several papers and Persian books on the above topics.

Mohammad H. Fardani holds a M.Sc. degree in civil engineering (construction engineering and management) from Islamic Azad University Khorasgan Branch, Isfahan, Iran. His research interests are concrete technology and soft computing. He has been working in construction projects in Isfahan.

Majid Ghanbari holds a M.A. degree in EMBA (Executive Master of Business Administration) from Islamic Azad University, Science and Research Branch, Shahrood, Iran. His research interests are soft computing, project management and business management. He has been working in Office of Real Estate of Municipality of District 5 in Tehran.