

A new approach to determination of compressive strength of fly ash concrete using fuzzy logic

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In this study, determination of effect of fly ash (FA) content on the compressive strength of concrete depending on water/cement ratio and concrete age was investigated by use of fuzzy logic (FL) approach. In the approach of modelling with FL, compressive strength values of various sample of concrete that produced by replacement of cement by F class of FA by ratio of 0 (control), 10%, 20% and 30% were used. Water/binder ratio of these concrete samples was varied between 0.27-0.60 in six different values. Experimental compressive strength values of the concrete specimens at 3, 7, 28, 90, 180 and 365 days compared with FL values obtained using the fuzzy sets. Optimum FA content and water/binder ratio for the best compressive strength for early age and hardened concrete can be obtained with FL.

Keywords: Fuzzy logic, Fly ash, Concrete, Compressive strength

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Introduction

Mineral admixtures, mostly pozzolanic materials, in cement and concrete include economic benefits and environmentally safe recycling of industrial and other waste by-products. Unlike chemical admixtures, they are used in relatively large amounts as replacement of cement with fine aggregate in concrete¹. Fly ash (FA) is a pozzolanic material widely used as a cement replacement to produce high-performance concrete and high-volume FA concrete. Benefits, in terms of the durability of high-strength concrete, are well established and the use of FA is now considered commonplace²⁻⁴.

FA is generally finer than Portland cement and ASTM specification C 618 defines two broad types of FA (Class F and Class C) related to the type of burned coal. Class F fly ash (CaO < 6%), designated as low calcium ashes, is not self-hardening but generally exhibits pozzolanic properties¹. At early ages, the strength of concrete containing high volumes of FA as a partial cement replacement is lower than that of control concrete; mainly due to slow pozzolanic reaction of FA⁵. One of the important properties needed for successful application of these materials in structures is compressive strength (CS)⁶. Actual CS of concrete is unknown during the early life of

structure⁷. Current empirical equations for estimating CS are based on tests of concrete without supplementary cementitious materials. The more one knows about the concrete composition versus strength relationship, the better one can understand the nature of concrete and how to optimize the concrete mixture^{8,9}.

The main contribution of FA to concrete, amongst others, is to the workability and the reduction of temperature rise in fresh concrete as well as to the durability and long term strength development of hardened concrete¹⁰. On the use of optimum FA in the concrete for the best CS, Öner *et al*¹¹ investigated the strength development of concrete containing FA and the optimum percent of FA in concrete. Han *et al*¹² predicted CS of FA concrete by apparent activation energy function. Papadakis & Tsimas¹³ an empirical formulation for the estimation of CS of FA concrete depending on concrete age and FA content has been developed¹⁴. Sebastiá *et al*¹⁵ developed a neural network based method to predict the unconfined CS of FA-cement mixtures.

This study presents new approach to determine CS of FA concrete using fuzzy logic (FL).

Experimental Study

A fuzzy logic system (FLS), which implements a nonlinear mapping between its inputs and outputs (Fig. 1), was used. Experimental variables were water-binder ratio (R), concrete age (Y) and FA Replacement

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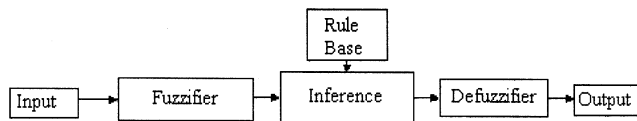


Fig. 1 — Schematic representation of a fuzzy logic system

Table 1 — Physical properties of Type II cement

Specific gravity	Specific Surface cm ² /g	Compressive strength MPa		
		3 days	7 days	28 days
3.15	3700	24.5	31.4	42.1

Table 2 — Experimental compressive strength results of FA concretes (MPa)

w/b	FA, %	Age of concrete, days					
		3	7	28	90	180	365
0.27	0	56.5	61.2	71.8	73.8	82	83.4
	10	49.9	56.6	67.7	75.4	85.2	87.4
	20	44	50.5	65	72.8	81.3	85.2
	30	34.5	40	51.9	60.4	70.8	78.6
0.32	0	45.9	52.2	62.1	63.3	71.2	71.4
	10	43.4	51.9	61.7	65.3	75.4	77.6
	20	39.6	46.6	58.6	66.1	78.1	78.9
	30	28.8	36.5	44.2	57.7	67.5	72.8
0.35	0	45	49.1	56.3	59.7	66.6	68.8
	10	39.5	50.2	55.7	64.3	72.4	74.8
	20	34.1	44.9	56	61.3	71.4	75.3
	30	27	39.1	51.8	59.5	68.9	73.9
0.4	0	34	43.6	49.7	54.6	60.4	61.9
	10	32.3	42.1	50.3	57.5	62.8	66.5
	20	29.3	38	48	56.1	61.4	65.4
	30	24.2	33.7	42.7	53.5	57.6	61.3
0.55	0	18.7	26.6	36.1	40.2	46.3	46.5
	10	16	25.4	38.3	45.8	49.6	51.8
	20	14.6	22.6	33.8	43.5	50	52.1
	30	12.7	18.3	30.9	39.3	47	48.2
0.6	0	15.4	23.6	32.9	38.6	41.6	42.5
	10	13.1	21.8	33.8	40.3	45.4	47.6
	20	10.2	18	28	37.2	41.6	44.8
	30	7.2	13.5	25	36	40.1	43.2

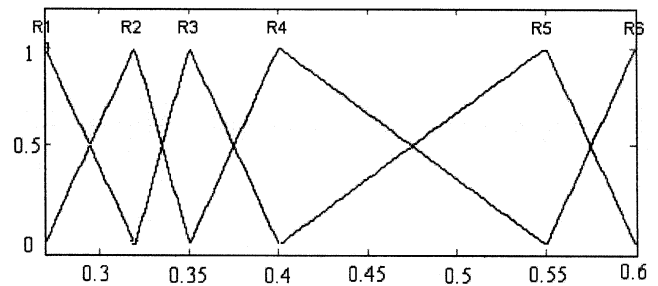


Fig. 2 — Membership functions for water/binder ratio

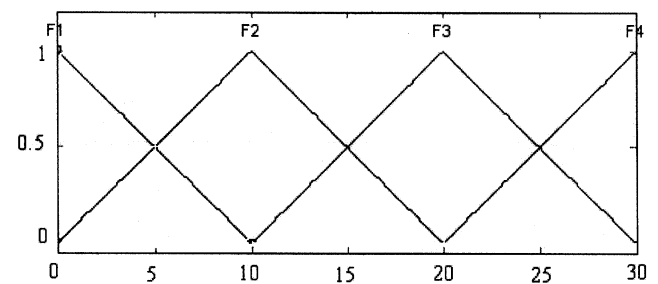


Fig. 3 — Membership functions for fly ash content

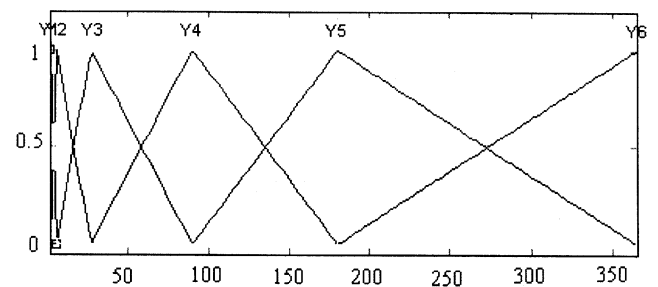


Fig. 4 — Membership functions for age of concrete

ratio. A MATLAB program was used for modelling the CS of FA concrete using FL. Type II cement was used. Physical properties of cement are given in Table 1¹². Specimens were wet cured at $21 \pm 2^\circ\text{C}$. Test ages of specimens were 3, 7, 28, 90, 180, and 365 days. Experimental CS value (C) of concrete depending on R, Y and FA content (F) were calculated (Table 2)¹².

In the input part of FL, three different factors were used as Y (3, 7, 28, 90, 180 and 365 days), R (0.27, 0.32, 0.35, 0.4, 0.55 and 0.6) and F (0, 10%, 20% and 30%). In the output part, one factor was used as C of FA concrete corresponding to different R. For different variables, membership functions were as follows: R (Fig. 2), 6 (R1, R2,..., R6); F (Fig. 3), 4 (F1, F2, F3, F4); Y (Fig. 4), 6 (Y1, Y2,..., Y6); and C (Fig. 5), 21 (C1, C2,..., C21).

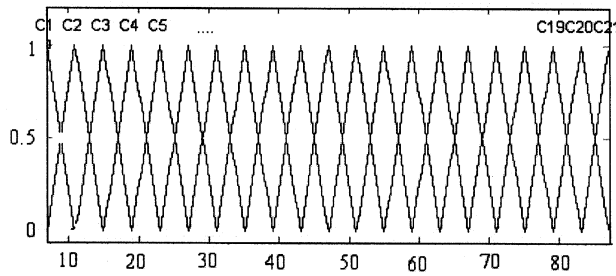


Fig. 5 — Membership functions for compressive strength of concrete

Table 3 — FL compressive strength results of FA concretes (MPa)

w/b	FA, %	Age of concrete, days					
		3	7	28	90	180	365
0.27	0	55	63	71	75	83	83
	10	51	55	67	75	85.9	85.9
	20	43	51	63	71	83	85.9
	30	35	39	51	59	71	79
0.32	0	47	51	63	63	71	71
	10	43	51	63	67	75	79
	20	39	47	59	67	79	79
	30	27	35	43	59	67	71
0.35	0	43	51	55	59	67	67
	10	39	51	55	63	71	75
	20	35	43	55	63	71	75
	30	27	39	51	59	67	75
0.4	0	35	43	51	55	59	63
	10	32	43	51	59	63	67
	20	31	39	47	55	63	67
	30	23	35	43	55	59	63
0.55	0	19	27	35	39	47	47
	10	15	27	39	47	51	51
	20	15	23	35	43	51	51
	30	11	19	31	39	47	47
0.6	0	15	23	31	39	43	43
	10	15	23	35	39	47	47
	20	11	19	27	39	43	43
	30	8.07	15	23	35	39	43

A rule base was formed by using Eq. (1) required for FL and inference was made after establishing input and output membership functions as

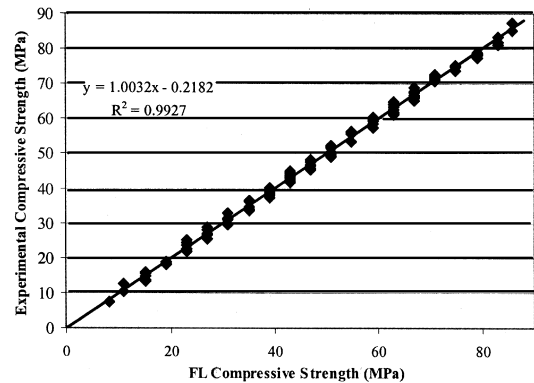


Fig. 6 — Comparison of experimental and fuzzy logic compressive strength results

IF $R=i$, $F=j$ and $Y=k$, THEN $C=p$ ($i=1, 2, \dots, 6$), ($j=1, 2, \dots, 4$), ($k=1, 2, \dots, 6$), ($p=1, 2, \dots, 21$) ... (1)

Then, the fuzzified output values from part of inference were defuzzified. For all F and Y , C values from the FL were defined separately and compared with experimental results. Also, error (E) was estimated by using Eq. (2)¹⁶.

$$E = \left(\frac{R_1 - R_2}{R_1} \right) \times 100 \quad \dots (2)$$

where, R_1 and R_2 are results of C from FL approach and from experimental study, respectively.

Results and Discussion

Early-age C values of FA concrete^{17,18} are smaller than that of the ordinary concrete but the long-term C values of FA concrete are larger than ordinary concrete. The 90 days C values of concrete with 10% FA replacement ratio are higher than that of concrete without FA (Tables 2 & 3). Therefore, it can be said that the FA replacement increases the long term C values of concrete^{11,12}. Also, the crossover effect of compressive strength of fly ash concrete becomes greater than that of ordinary concrete with aging is delayed as the fly ash replacement ratio increases.

A good linear relationship between experimental and FL results of C values of FA concrete was observed with correlation coefficient of 0.99 (Fig. 6). FL was successful in learning the relationship between the different input parameters such as F , R , Y and output parameters as C value.

Prediction model gives very close estimates of CSs of concrete containing FA (Fig. 7). The difference between predicted and experimental CSs of concretes

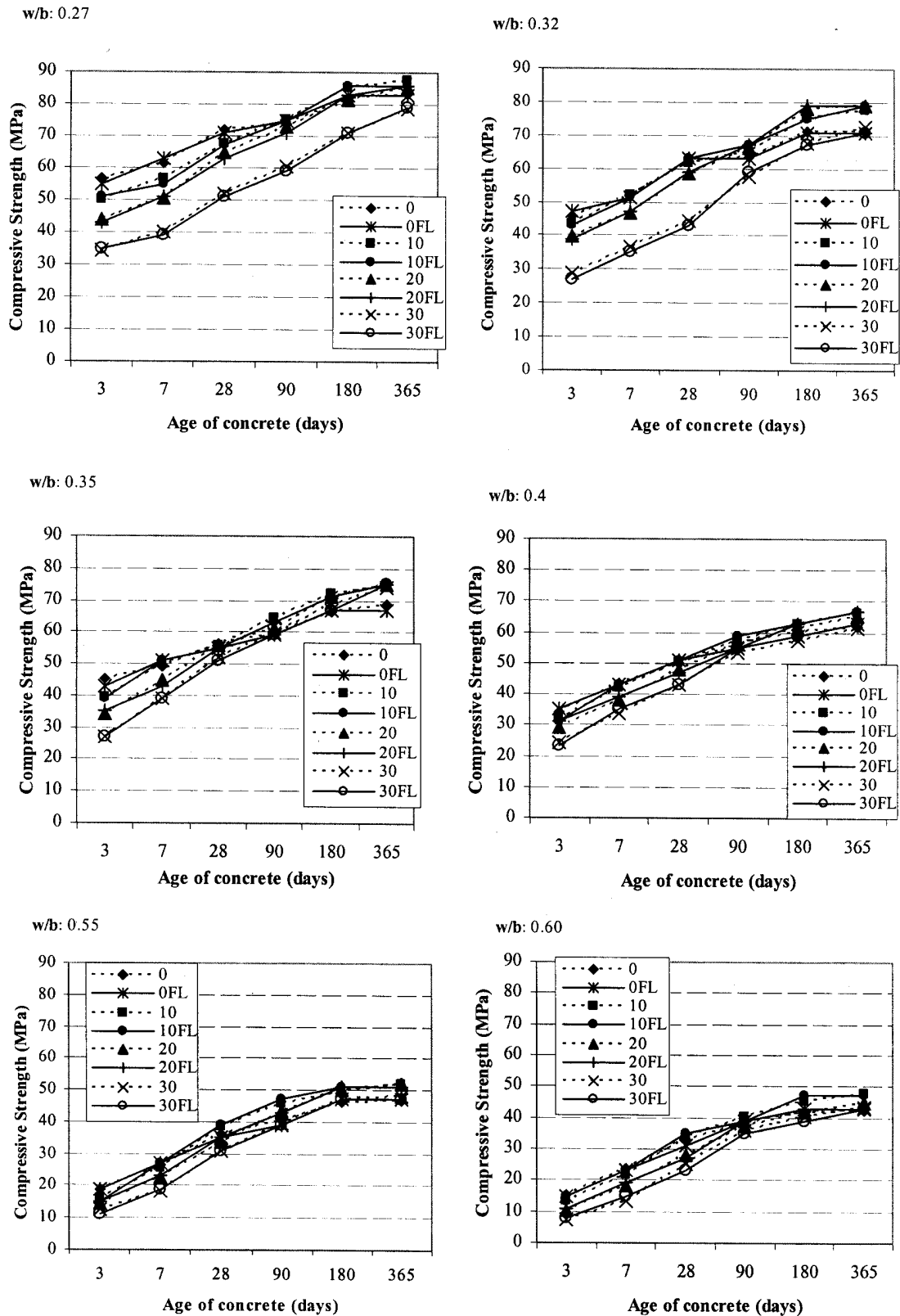


Fig. 7 — Comparison of experimental and fuzzy logic compressive strength values related with fly ash content and concrete age for every water/binder ratio

Table 4 — Error estimation of experimental and FL results

w/b	FA, %	Age of concrete, days					
		3	7	28	90	180	365
0.27	0	-2.73	2.86	-1.13	1.60	1.20	-0.48
	10	2.16	-2.91	-1.04	-0.53	0.81	-1.75
	20	-2.33	0.98	-3.17	-2.54	2.05	0.81
	30	1.43	-2.56	-1.76	-2.37	0.28	0.51
0.32	0	2.34	-2.35	1.43	-0.48	-0.28	-0.56
	10	-0.93	-1.76	2.06	2.54	-0.53	1.77
	20	-1.54	0.85	0.68	1.34	1.14	0.13
	30	-6.67	-4.29	-2.79	2.20	-0.75	-2.54
0.35	0	-4.65	3.73	-2.36	-1.19	0.60	-2.69
	10	-1.28	1.57	-1.27	-2.06	-1.97	0.27
	20	2.57	-4.42	-1.82	2.70	-0.56	-0.40
	30	0.00	-0.26	-1.57	-0.85	-2.84	1.47
0.4	0	2.86	-1.40	2.55	0.01	-2.37	1.75
	10	-0.01	2.09	1.37	2.54	0.32	0.75
	20	5.16	2.56	-2.13	-0.02	2.54	2.39
	30	-5.22	3.71	0.47	2.73	2.37	2.70
0.55	0	1.58	1.48	-3.14	-3.08	1.49	1.06
	10	-6.67	5.93	1.79	2.55	2.75	-1.57
	20	2.67	1.74	3.43	-1.16	1.96	-2.16
	30	-15.45	3.68	0.32	-0.77	0.00	-2.55
0.6	0	-2.67	-2.61	-6.13	1.03	3.26	1.16
	10	12.67	5.22	3.43	-3.33	3.40	-1.28
	20	7.27	5.26	-3.70	4.62	3.26	-4.19
	30	10.78	10.00	-8.70	-2.86	-2.82	-0.47

increases with increasing of FA replacement content and water-binder ratio. CS gain for concrete with water-binder ratio less than 0.32 varies considerably at early ages (< 7 days) and later ages (> 180 days).

On comparing C values versus Y for all Rs, it was observed that there was very close relationship between results obtained from experimental and FL approach (Fig. 7). Highest error (-15.45) was obtained in 30% FA content and 0.55 R at 3 days (Table 4). Furthermore, average error was obtained as 2.46%.

However, the difference is not large between experimental results and the prediction model results.

Conclusions

Fuzzy logic based model has been developed for estimating the compressive strength of fly-ash based concrete. A good linear relationship between experimental and FL results of C values of FA concrete was observed. The prediction model properly estimates the compressive strength of fly ash containing concrete in maximum error of -15.45%. The difference between predicted and experimental compressive strengths of concretes increases with increasing of fly ash replacement content and water-binder ratio. In general, concrete is a highly complex material and prediction of the best compressive strength of fly-ash concrete is quite difficult task to model. The proposed fuzzy logic model will save time, reduce wastage of material and reduce the design cost.

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