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Strength prediction of fly ash concretes by accelerated testing

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Abstract

Relationships between standard compressive strength at 7, 28, and 90 days and early strength attained by (1) autogeneous curing, (2) warm water curing, and (3) boiling water curing were obtained and a regression expression to predict the strength of concretes containing high-lime and low-lime fly ashes as partial cement replacement are proposed. The control concretes were designed for 28-day characteristic compressive strengths, f_{ck28} = 40, 60, 65, and 70 MPa. All concretes were proportioned to keep the slump at 80–100 mm. The curing methods used were in accordance with the relevant ASTM and Turkish standards.

Keywords: Fly ash; Concrete; Acceleration; Curing; Compressive strength

1. Introduction

Usually, the criterion for the quality of concrete is based on the 28-day compressive strength of standard cylinder or cube specimens cast, cured, and tested under controlled conditions. Currently, however, the increasing speed of construction calls for the potential strength of concrete to be determined at the earliest possible time after the concrete has been placed.

Moist-cured test specimens do not always give reliable results at very early ages since slight changes in the first few hours after casting my have considerable effects on early strength [1]. Therefore, methods for earlier determination of concrete strength with satisfactory reliability had been researched for over 30 years. The first reported study on accelerated-strength determination dates back to 1927 [2]. After a dormant period of about 30 years, systematic efforts on the subject were made in many research centers [3,4]. Today, there are three basic accelerated curing procedures described in ASTM and Turkish standards: (1) autogeneous curing, (2) warm water curing, and (3) boiling water curing.

The object of this study was to investigate the relationships between the standard 28-day and accelerated compressive strengths of concretes made with an ordinary Portland cement (PC) and different amounts of two high-lime and two low-lime fly ashes ,and to propose a strength prediction expression for fly ash concrete strengths at different ages.

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2. Methods

2.1. Materials and mix proportions

The cement used was an ordinary PC. Two high-lime (HL1 and HL2) and two low-lime (LL1 and LL2) fly ashes were used as partial cement replacement. The properties of

Table 1
Properties of cement and fly ashes used

	Chemical composition				
Oxide (%)	PC	HL1	HL2	LL1	LL2
CaO	63.3	20.3	14.0	4.4	2.0
SiO_2	20.2	43.3	47.1	58.6	59.4
Al_2O_3	5.9	25.1	17.4	21.9	25.8
Fe_2O_3	3.3	4.9	8.3	9.3	5.8
MgO	1.8	0.8	1.9	1.4	0.6
SO_3	2.9	2.5	4.6	0.4	0.1
K_2O	0.8	1.3	1.8	1.8	3.8
Na_2O	0.5	0.2	2.4	0.3	0.4
LOI	0.8	1.19	1.7	1.4	1.6
IR	0.4	nd	nd	nd	nd
Physical and mechanical properties					
Compressive strength (MPa)					
7 days	20.7				
28 days	31.6	–	–	–	–
90 days	42.9				
Density (g/cm^3)	3.12	2.25	2.28	2.08	2.02
Blaine fineness (m^2/kg)	292	455	275	302	290
PAI with PC (%)	–	84.5	61.0	66.3	54.7
PAI with lime (MPa)	–	32.0	17.3	14.7	9.3

nd = not determined. PAI = Pozzolanic activity index.

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Table 2
Mix proportions of control concretes

Mix	Cement (kg/m^3)	Net mixing water (kg/m^3)	0–4 mm sand (SSD) (kg/m^3)	4–8 mm crushed stone (SSD) (kg/m^3)	8–16 mm crushed stone (SSD) (kg/m^3)	HRWRA (kg/m^3)
C1	387	184	551	282	964	–
C2	426	115	535	270	926	30
C3	453	120	511	264	898	31.7
C4	512	130	500	256	877	35.8

SSD = Saturated surface dry. HRWRA = High range water reducing agent.

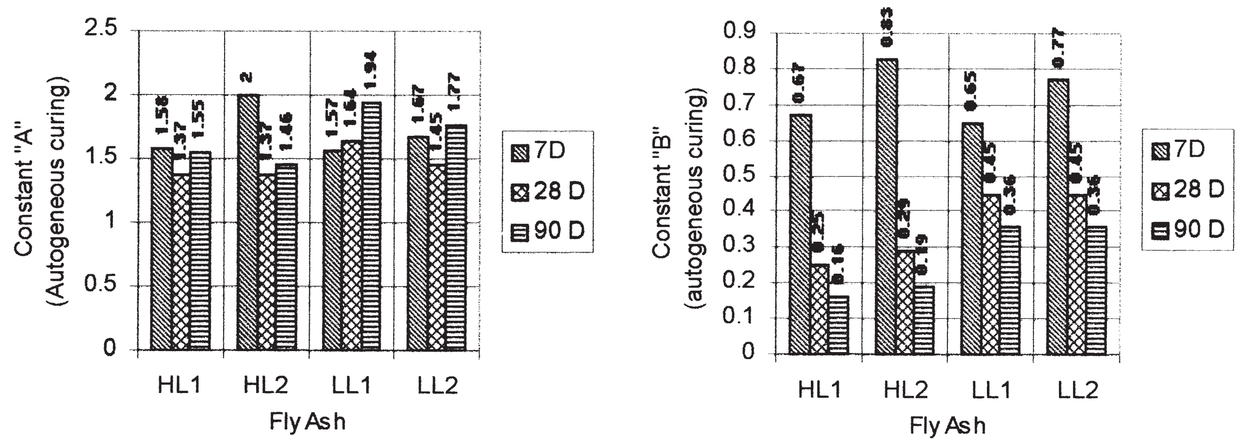

Fig. 1. Constants *A* and *B* for different fly ashes under autogeneous curing.

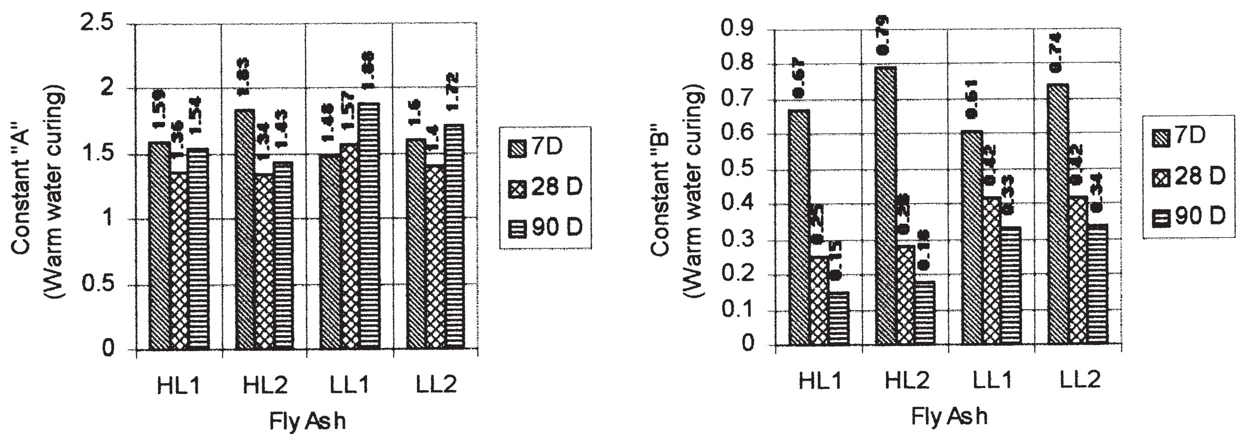

Fig. 2. Constants *A* and *B* for different fly ashes under warm water curing.

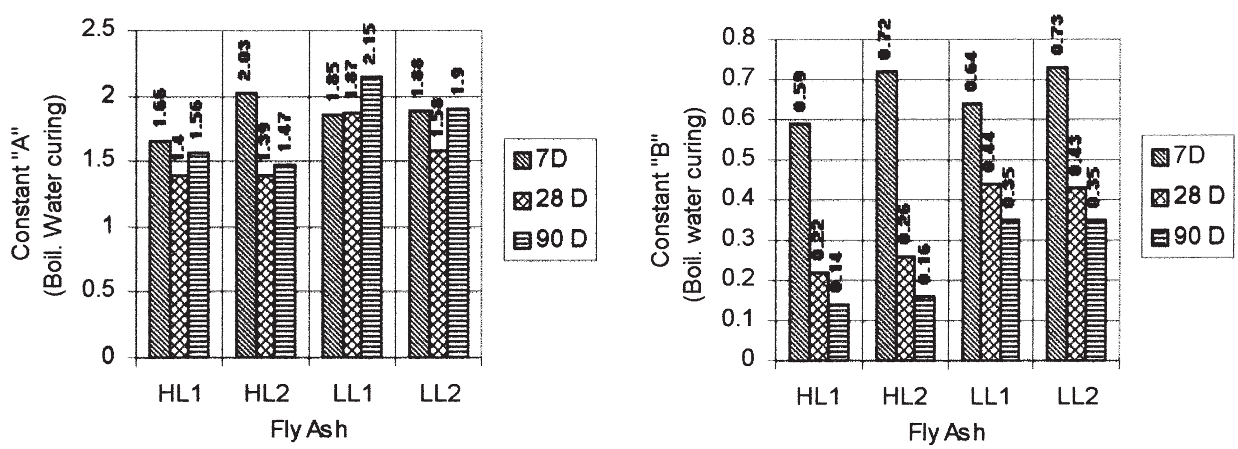

Fig. 3. Constants *A* and *B* for different fly ashes under boiling water curing.

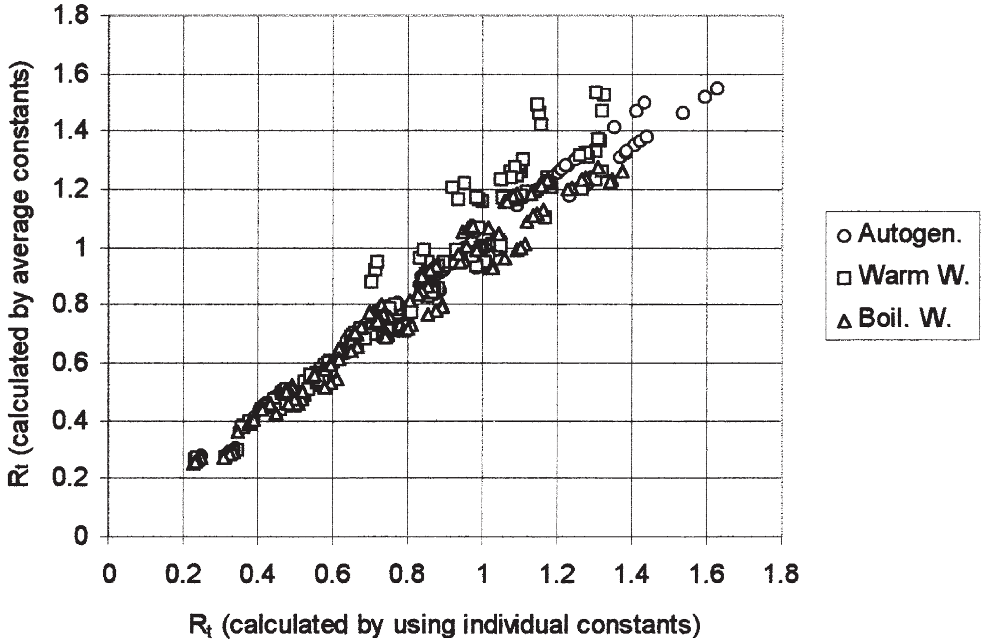

Fig. 4. Comparison of R_t values calculated by using individual constants for each fly ash and average constants for high-lime and low-lime fly ash groups.

the cement and mineral admixtures used are given in Table 1. In superplasticized mixes a melamine-formaldehyde-based high range water reducing agent (HRWRA) was used at 3, 5, and 7% by weight of cement.

The fine aggregate was a natural river sand and the coarse aggregate was crushed limestone. Maximum aggregate size was 16 mm.

The control mixes C1, C2, C3, and C4 were designed to obtain 28-day characteristic compressive strengths of 40, 60, 65, and 70 MPa, respectively. Mix proportions of the control concretes are given in Table 2. Fly ashes were used to replace 10, 20, and 40% (by weight) of PC in fly ash-incorporated mixes. In all mixes the slump was kept at 80–100 mm and water contents were adjusted accordingly. Thus, 52 different concrete mixes (including the four control mixes) were prepared.

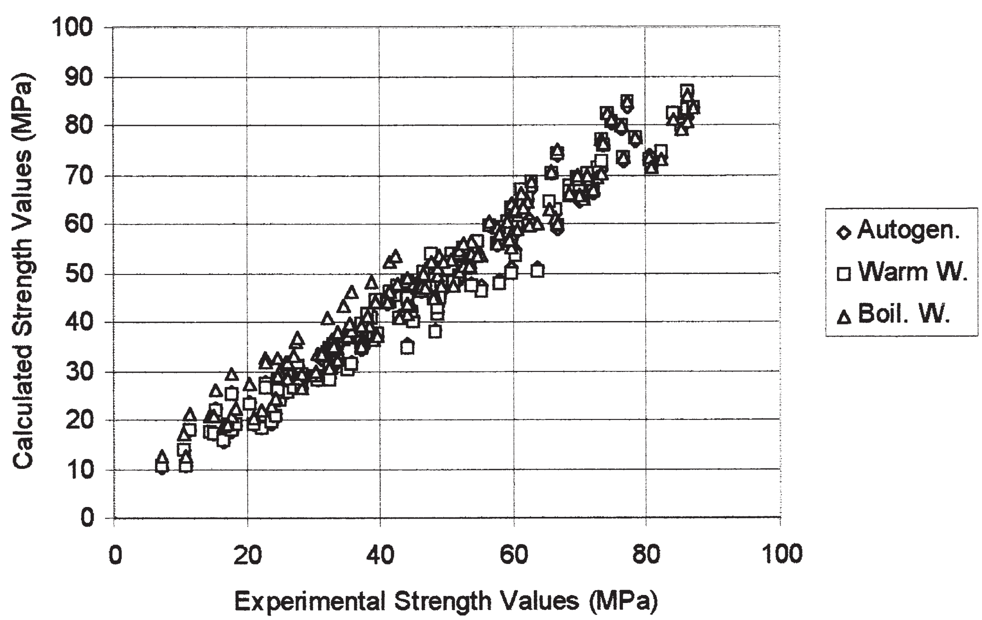

Fig. 5. Comparison of experimental and calculated strength values.

Table 3
Compressive strength test results after standard moist curing for 7, 28 and 90 days and after autogeneous, warm water and boiling water curing[a]

Mix no.	Standard moist curing (MPa)			Accelerated curing (MPa)		
	f_7	f_{28}	f_{90}	f_{auto}	f_{ww}	f_{bw}
C1	22.7	37.3	43.2	12.1	14.3	13.0
C2	49.8	59.2	75.9	25.5	26.2	18.7
C3	53.7	65.9	80.7	33.2	31.3	21.6
C4	54.4	69.9	82.0	38.7	34.7	23.9
10HL11[b]	24.6	38.5	46.1	12.1	12.2	11.5
10HL12	55.3	62.4	80.4	20.2	19.3	15.5
10HL13	59.7	68.5	84.0	21.6	22.9	16.4
10HL14	60.5	72.7	86.3	23.3	23.8	17.2
10HL21	20.4	33.6	39.4	9.3	9.6	6.9
10HL22	44.2	53.8	69.6	13.7	13.8	10.2
10HL23	48.3	59.1	73.3	14.8	15.0	11.5
10HL24	48.6	62.1	74.2	16.4	16.8	12.7
10LL11	22.8	37.4	46.8	12.4	12.7	9.6
10LL12	48.5	59.8	82.2	19.4	20.2	14.3
10LL13	58.0	66.3	86.1	21.7	22.7	15.7
10LL14	63.6	70.5	86.2	22.8	22.9	16.7
10LL21	22.9	32.3	41.4	12.0	12.1	9.0
10LL22	44.9	50.9	73.2	17.7	18.4	12.8
10LL23	48.9	56.6	76.2	19.8	20.1	15.2
10LL24	53.7	59.8	77.1	20.8	21.3	16.2
20HL11	17.8	37.2	48.0	10.4	10.1	7.9
20HL12	38.6	59.5	80.7	17.1	17.4	12.6
20HL13	41.5	65.4	85.4	18.3	18.9	13.9
20HL14	42.2	68.4	87.1	18.4	18.3	14.2
20HL21	15.3	33.0	41.2	8.7	8.9	7.1
20HL22	32.0	52.1	69.6	13.3	13.1	10.7
20HL23	34.5	57.7	73.7	13.9	13.6	10.7
20HL24	35.8	60.5	74.8	14.7	15.0	11.5
20LL11	14.4	28.1	39.6	6.6	6.4	4.8
20LL12	30.5	44.7	66.6	10.6	10.2	8.1
20LL13	32.6	49.3	69.9	11.3	12.1	8.7
20LL14	33.5	51.9	71.2	11.8	11.9	9.2
20LL21	11.3	24.7	35.3	6.7	6.1	5.9
20LL22	25.8	38.0	58.1	9.8	9.9	7.3
20LL23	27.2	42.7	61.3	11.1	11.6	8.8
20LL24	27.6	44.2	62.8	11.2	11.1	8.7
40HL11	15.1	32.3	43.0	6.1	5.8	4.1
40HL12	32.4	52.5	72.1	10.3	10.4	8.3
40HL13	35.1	57.7	76.5	10.9	11.1	8.5
40HL14	35.7	60.7	78.3	11.2	11.5	8.5
40HL21	10.5	27.7	37.1	4.6	4.8	3.2
40HL22	24.9	45.6	61.7	8.3	8.1	5.7
40HL23	26.0	49.4	65.7	8.7	8.4	6.4
40HL24	26.9	52.5	66.6	8.9	8.8	7.0
40LL11	10.8	21.1	30.3	3.2	2.9	2.6
40LL12	22.2	33.6	51.0	5.7	5.4	4.1
40LL13	23.7	37.1	53.6	5.8	5.6	4.3
40LL14	24.3	39.0	54.6	6.2	6.1	4.3
40LL21	7.1	17.1	26.0	3.1	2.9	2.3
40LL22	16.4	28.2	44.0	4.6	4.3	3.3
40LL23	17.7	31.3	46.6	5.1	4.9	3.9
40LL24	18.4	33.0	47.6	5.5	5.4	4.0

[a] Each data value is an average of six specimens.

[b] Designation indicates 10% cement replacement by HL1 fly ash in C1 mix.

2.2. Curing methods

Thirty-six specimens were prepared from each mix and six specimens were used for each curing condition and at each age of testing. The specimens were cured under four different conditions: (1) Standard moist curing: the specimens were kept in the curing room at 23 ± 1.7°C and 95 + 5% relative humidity (RH) until the time of test (7, 28, and 90 days); (2) Autogeneous curing (Auto): the molded specimens were sealed in plastic bags and placed in autogeneous curing chamber for 46 h and strength tests were carried out at 49 h, 15 min; (3) Warm water curing (W.W.): immediately after casting, the sealed cylinder molds were immersed into 35°C water. The specimens stayed in warm water for 24 h and were tested at 26 h, 15 min after casting; (4) Boiling water curing (B.W.): the sealed molds were kept in moist curing room for 23 h. They were then immersed in boiling water for 3.5 h. Tests were carried out at 28.5 h, 15 min after casting.

3. Results and discussion

The test results are given in Table 3. Carrying out regression analyses using the data given, the relationship between accelerated strength and standard strength upon moist curing was obtained as a power equation, as seen in Eq. (1):

$$R_t = A(R_a)^b \tag{1}$$

where R_t is the ratio of compressive strength of fly ash concrete at age t to the 28-day compressive strength of the control concrete; R_a is the ratio of the accelerated-strength fly ash concrete to the 28-day compressive strength of the control concrete; and A and B are constants depending on type of fly ash and age.

This relationship is in agreement with the findings of other researchers [5–8]. The constants A and B of the above equation at 7, 28, and 90 days for four different types of fly ashes used and autogeneous, warm water, and boiling water curing methods are given in Figs. 1, 2, and 3, respectively. Both constants depend on age and the type of fly ash used. It was observed that the constants obtained for the three different accelerated curing conditions employed were close to each other. There seems to be a decrease in constant A from 7 to 28 days and an increase thereafter. At 7 days, constant A is slightly greater for high-lime fly ashes. At 28 and 90 days, however, it is greater for low-lime fly ashes. Constant B, on the other hand, decreases with age. The rate of decrease is higher in high-lime fly ash concretes than in low-lime fly ash concretes.

From a practical point of view, using the average values of the constants given in Figs. 1, 2, and 3 was found to be appropriate instead of using individual values, which are very close to each other for the two fly ashes in each group. These values are given in Table 4. Comparison of R_t values obtained by using the individual constants for each fly ash and average constants for the two groups of fly ashes given in Fig. 4 supports this reasoning. Furthermore, comparison of the experimental and calculated strength values shown in Fig. 5 indicates that the power equation proposed for predicting the strength of fly ash concretes by accelerated tests

Table 4
Average values of the constants *A* and *B* for high-lime and low-lime fly ashes at different ages and for three different accelerated curing methods used

	Constant *A*						Constant *B*					
	HL			LL			HL			LL		
Age (days)	Auto.	W.W.	B.W.	Auto.	W.W.	B.W.	Auto.	W.W.	B.W.	Auto.	W.W.	B.W.
7	1.79	1.71	1.84	1.62	1.54	1.86	0.75	0.73	0.66	0.71	0.68	0.69
28	1.37	1.35	1.39	1.55	1.49	1.72	0.27	0.27	0.24	0.45	0.42	0.44
90	1.51	1.48	1.52	1.85	1.80	2.03	0.18	0.17	0.15	0.36	0.34	0.35

is reliable: 94.4% of the values calculated by using the autogeneous curing test results were within ±20% of the experimental results. This is 93.8 and 84% for warm water curing and boiling water curing, respectively.

The proposed relationship is independent of the amount of fly ash used. Once the 28-day compressive strength of the control concrete is known and the accelerated strength of the fly ash-incorporated concrete is obtained, the 7-, 28-, and 90-day strengths of the fly ash concretes can be estimated by using the proposed power equation.

4. Conclusions

The following conclusions were drawn from the results of this investigation:

1. The relationship between accelerated strength and standard strength in fly ash concretes can be represented by a power equation, the constants of which depend on the type of fly ash used and the age of concrete.
2. Once the 28-day strength of the control concrete without fly ash is known and the accelerated strength of the corresponding fly ash concrete is obtained, the standard strength of the fly ash concrete can be predicted with sufficient reliability by using the proposed relationship. The amount of fly ash used is immaterial.
3. The constants of the proposed power equation do not vary significantly under different accelerated curing conditions. Therefore, the same relationship may be used for different accelerated curing methods. However, it is more dependable for autogeneous and warm water curing than for boiling water curing.

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