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Prediction of compressive strength of concrete with fly ash as sand replacement material

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Abstract

Fly ash (FA) acts as a partial replacement material for both Portland cement and fine aggregate. The published information on FA as sand (fine aggregate) replacement material (SRM) is limited and rational guidelines to estimate the compressive strength of concrete are not available. This aspect was investigated and a formula to predict the compressive strength of concrete at 28 day is suggested in this paper. This formula, containing cementing efficiency factor, k, of FA, is useful also when the quantity of FA used is more than that of sand replaced. Application of the formula to the test data in published literature, indicate that it can estimate the compressive strength of concrete containing different levels of sand replacement by fly ash.

Keywords: Fly ash; Sand; Cementing efficiency; Strength; Concrete

1. Introduction

Fly ash (FA) as a cementitious material has been studied extensively [1–3] and it is observed that FA refines the microstructure of Portland cement matrix and thereby enhancing the durability [4,5]. Many standard codes of practice recommend use of FA as mineral admixture (to become part of binder system) in concrete [6] and several important structures of different varieties (Petronos Towers, Great Belt Bridge, Euro Tunnel, etc.) are already built. However, only limited studies are reported on direct role of FA as a fine aggregate (i.e., sand) and also as a "sand replacement material" (SRM); guidelines to predict the strength of concrete containing FA as SRM are not widely available. This aspect was studied at the Structural Engineering Research Centre (SERC), Chennai, India, and the test data indicated that 'cementing efficiency factor' of FA can be used to evolve a formula based on the Bolomey equation [7] to estimate the compressive strength of concretes when sand is replaced partially by FA. Applicability of this Prediction Equation to the test results published by various authors is also presented.

2. Literature review

Dhir et al. [8] studied concretes (with $w/c = 0.50$) of three different coarse aggregate (CA) contents having FA as SRM at the FA/Sand ratios of 0.05, 0.10 and 0.15. Significant improvements in compressive strengths at all the ages were reported even though the workability of mixes was affected.

Mangaraj and Krishnamoorthy [9] reported on sand replacement levels (SRLs) of 0–30% for the basic concrete having a w/c ratio of 0.60. A need to increase the water content for compensating adverse effects of FA on workability of concrete was observed and however, compressive strengths were found to be enhanced.

Rafat Siddique [10] presented an extensive data on effects of replacements of fine aggregate with Class F fly ash for a concrete with w/c ratio of 0.47 at ages from 7 to 365 day. At SRLs of 10–50%, the workability of

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concretes were lowered, but, compressive strengths were improved.

Maslehuddin [11] showed that FA at SRLs of 20% and 30% increases early age compressive strengths (and also long term corrosion resistance) of concretes at w/c ratios of 0.35–0.50.

Berg and Neal [12] confirmed the potential of ash from burning of municipal solid waste as fine aggregate in concrete.

The experimental work by Hwag et al. [13] on carbonation and strength development in mortars containing FA at SRLs of 25% and 45% indicated that improvement in properties occur in mortars with w/c ratios of 0.30–0.50.

Increases in compressive and tensile strength of concrete with FA as SRM were reported by Bakoshi et al. [14].

A look at the test results reported in the literature indicate that generally there was no effort to formulate a methodology so that FA as SRM did not affect the strengths; very often, the strengths of concretes containing FA were more than that of cement concretes. Guidelines for prediction of strengths of concrete with FA as SRM were also not explicitly formulated. Therefore, suggestions for modifying the basic cement concrete to get a concrete containing FA at a desired SRL, are made in the present paper; the attempts are also made to evolve a prediction formula to estimate the strength of concrete having sand replaced partially by a known amount of fly ash. The use of fly ash as SRM can refine the microstructure, enhance durability, make concrete less energy intensive and more eco-friendly, as observed in concretes containing FA as partial cement replacement material [15–17].

3. Scope of work

A cement concrete (CC), Mix S_0, with proportions of cement:sand:coarse aggregates:water = 1:1:2:0.35 was considered. Fly ash concretes (FACs) with FA at SRLs of 20%, 40%, and 60% were prepared and at each SRL, three water–cement ratios were chosen. Actual FA quantity added was varied from 1.0 to 1.6 times the quantity of sand replaced to study the effect of higher quantity of fly ash in concrete. Compressive strength of these mixes (S_1–S_{27}) was determined at 28 day and a prediction formula to estimate strength of FACs having FA as SRM was evolved. This formula utilises the cementing efficiency factor, k, of the FA, which depends on fraction of FA in the binder.

4. Details of experimental work

A ribbon mixer with horizontal shaft was used to mix the concrete mix. Specific gravity and fineness modulus of sand and coarse aggregates were 2.64, 2.2, and 2.81, 6.5, respectively. Carboxylic Ester based SP satisfying IS: 9103 were used. Details of binders and mixes are given in Table 1. A mixing time of about 2 min was enough to get a uniform concrete mix. Cube specimens (size 100 mm) were cast in steel moulds and table vibrator was adequate for compacting. Demoulding could be carried out after 24 h of casting and curing was effected by storing the specimens under water. A minimum of three specimens was used in each test.

5. Test results and discussion

5.1. Derivation of strength prediction formula

Bolomey [7] had proposed following equation for prediction of strength of cement concrete (CC):

$$f_c = A * (C/W) + B = A * (1/wc) + B \quad (1)$$

where, constants A and B depend mostly upon the age and type of cement, C, W = cement and water contents, $wc = W/C$ = water–cement ratio.

It is shown by Brandt [18] that the above equation can be simplified in many cases by substituting $B = -0.50 * A$, for structural grade concretes as

$$f_c = A * \{(C/W) - 0.50\} \quad (2a)$$
$$= A * \{(1/wc) - 0.50\} \quad (2b)$$

Investigations by Larrard [19], Smith [20], Ganesh Babu and Sivanageswara Rao, [21], Hanson and Hedegaard, [22], etc. have shown that when FA becomes part of binder portion of concrete, its contribution to strength of concrete can be accounted by a factor, k, known as "cementing efficiency of fly ash" and therefore, Eq. (2) can be rewritten for fly ash concrete (FAC), as given below, by substituting C with 'equivalent cement content' C_{eq}

$$C_{eq} = (1-p) * B + k * p * B = (1 - p + k * p) * B$$
$$= [1 - p * (1-k)] * B \quad (3)$$

$$f_c = A * \{(C_{eq}/W) - 0.50\}$$
$$= A * \{([1 - p * (1-k)] * B/W) - 0.50\}$$
$$= A * \{([1 - p * (1-k)]/wb) - 0.50\} \quad (4a)$$

where, in FAC, B, C, F, W = binder, cement, fly ash and water contents, $B = C + F$, $wb = W/B$ = water–binder ratio, p = fly ash fraction of binder = F/B, $(1-p)$ = cement fraction of binder = C/B.

Comparing Eqs. (2b) and (4a), it is seen that

$$wb = [1 - p * (1-k)] * wc \quad (4b)$$

Thus, for equivalent strength in CC and FAC, the wb of FAC is different from wc of CC depending upon the value of 'k'. Consider a CC with unit contents of ingredients as:

Cement : sand : coarse aggregate : water

$$= C : S : CA : W \ \mathrm{kg/m^3} \quad (5a)$$

Then, weight proportions of ingredients will be

Cement : sand : coarse aggregate : water

$$= 1 : S/C : CA/C : W/C = 1 : s : ca : wc \quad (5b)$$

where $s = S/C$ = sand fraction in concrete, $ca = CA/C$ = coarse aggregate fraction in concrete.

Table 1a
Details of binder system and concrete mixes: properties of cement and fly ash

S. no.	Property	Ordinary portland cement	Fly ash
1	Type	OPC (43 grade) (IS: 8112)	Class F
3	Specific gravity	3.15	2.2
4	Blaine fineness	295 m^2/kg	310 m^2/kg
5	Standard consistency	31%	–
6	28 day Compressive strength (IS:4031)	49 MPa	–
8	Bulk density	1550 kg/m^3	995 kg/m^3

Table 1b
Details of binder system and concrete mixes: chemical composition of fly ash

S. no.	Components	IS 3812 (2003)	Fly ash used (%)
1	$SiO_2 + Al_2O_3 + Fe_2O_3$	70% min	96
2	SiO_2 (alone)	35% min	59
3	MgO	5% max	0.30
4	Total sulphur as SO_3	2.75% max	–
5	Alkalies as Na_2O	1.5% max	0.54
6	LOI	12% max	1.08%
7	CaO	–	1.02
8	K_2O	–	0.25

Table 1c
Details of binder system and concrete mixes: details of basic cement concrete mix, S_0

(i) Cement:sand:coarse aggregate:water:superplasticiser
= C:S:CA:W:SP (unit contents of concrete)
= 561:561:1121:196:0.85 kg/m^3
= 1:s:ca:wc:sp (weight proportions)
= 1:1:2:0.35:0.0015
(ii) Fresh concrete density = 2442 kg/m^3, workability=125 mm (slump)
(iii) Compressive strength, MPa = f_c = 35 at 7 day and 46 at 28 day
(iv) Values of 'A' in Bolomey equation for the concrete
Bolomey equation (Brandt), $f_c = A * \{(C/W)-0.50\} = A * \{(1/wc) - 0.50\}$, A = 14.42, 19.23 at 7 and 28 day respectively

If p_s fraction of sand in concrete is replaced by FA, then,

$$\text{proportion of sandin concrete} = (1-p_s)*s \quad (6a)$$

To achieve more usage of FA in content (so that disposal problem of FA is partially mitigated), the actual quantity of FA added could be more than that of reduction in sand content. Then,

$$\text{Actual proportion of FA used} = p = m*p_s*s \quad (6b)$$

where, $m > 1$ and it can be referred as 'fly ash addition factor' (FAF).

Therefore, from Eqs. (5b), (6a) and (6b), proportions of the fly ash concrete (FAC) having FA as SRM, are

$$[\text{Cement : fly ash}] : [\text{sand}] : [\text{coarse aggregate}] : [\text{water}] = [1 : (m*s*p_s] : [(1-p_s)*s] : [ca] : [wc] \quad (7a)$$

We may note that for the FAC having FA as SRM, the water–binder ratio could be calculated from Eq. (4b). When FA is taken as part of binder, then, Eq. (4a) can be used.

From Eq. (7a), we can compute the following:

$$p = \text{fly ash fraction in binder} = \text{fly ash/binder} = \text{fly ash}/(\text{cement} + \text{fly ash}) = (m*s*p_s)/[1+(m*s*p_s)] \quad (7b)$$

$$(1-p) = \text{cement fraction in binder} = \text{cement/binder} = \text{cement}/(\text{cement} + \text{fly ash}) = 1/[1+(m*s*p_s)] \quad (7c)$$

$$wb = \text{water–binder ratio in FAC} = \text{water/binder} = \text{water}/(\text{cement} + \text{fly ash}) = wc/[1+(m*s*p_s)] \quad (7d)$$

Substituting Eqs. (7b), (7c) and (7d) in Eq. (4a), we get,

$$f_c = A*\{([1-p*(1-k)]/wb) - 0.50\} \quad (8a)$$
$$= A*\{[(1+m*p_s*s*k)/wc] - 0.50\} \quad (8b)$$

6. Applicability of prediction formula to FAC mixes with FA as SRM

6.1. Cementing efficiency of fly ash 'k'

In the present study, an analysis of several test results available on the Class F FA used at SERC, Chennai, India, indicated that variation of 'k' with fly ash fraction, p, in

Table 2
Computation of 'cementing efficiency of fly ash', k

P	10	20	30	40	50	60	70	80
k at 7 day	0.67	0.6	0.56	0.53	0.51	0.49	0.48	0.46
k at 28 day	0.88	0.78	0.72	0.68	0.65	0.63	0.61	0.59

k at 7 day strength of FACs = $0.90 - 0.10 * \log_e(P)$.
k at 28 day strength of FACs = $1.20 - 0.14 * \log_e(P)$.
$P = 100 * p$, p = fly ash fraction in binder portion of concrete.

binder portion of concrete at any age could be represented by

$$k \text{ at any age of FAC} = a + b * \log_e(100 * p) \quad (9a)$$
$$= a + b * \log_e(P) \quad (9b)$$

where p = fraction of FA in binder = $F/B = F/(F + C)$ and $P = 100 * p$.

Constants 'a' and 'b' of Eq. (9) can be evaluated by the data on concretes with and without FA. For the fly ash used in the present study, constants of above equation are given in Table 2 and the variation of 'k' with 'P' is shown in Fig. 1. It may be noted here that the values for 'a' and 'b' in Table 2 is valid for the FA is used in the present study and it is necessary to find out the constants for any other fly ash.

6.2. Value of 'A' in prediction equation

This depends upon type/strength of cement and age of concrete. In the present study, the values of 'A' at 7 day and 28 day were found out by applying Eq. (2b) to CC Mix S_0, where there is no FA (Table 1c). These values of 'A' were used in computations for the FAC mixes (Table 3).

P	10	20	30	40	50	60	70	80
k_{7d}	0.66974	0.60043	0.55988	0.53111	0.5088	0.49057	0.47515	0.4618
k_{28d}	0.88	0.78	0.72	0.68	0.65	0.63	0.61	0.59

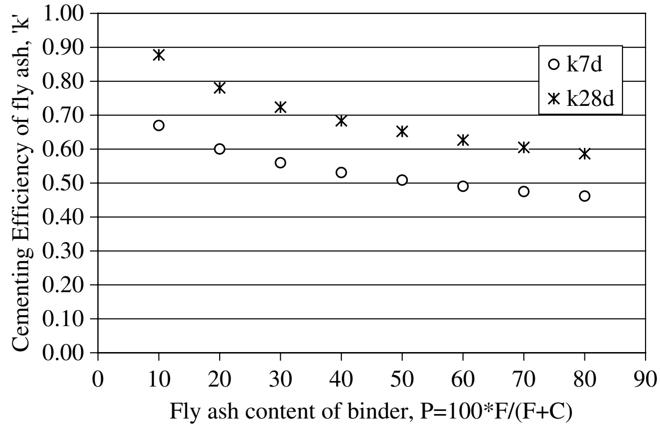

Fig. 1. Relationship between fly ash content, P and cementing efficiency of fly ash, 'k'.

Table 3
Comparison between compressive strengths from tests and prediction formula

Mix ID	FCD (kg/m^3)	wb	wc	FAF m	SRL ps	FF p	k for FACS		f_{test}, MPa		f_{eqn}, MPa		%Difference	
							7 day	28 day	7 day	28 day	7 day	28 day	7 day	28 day
S_0	2442	0.35	0.35	0.00	0.00	0.00	1.00	1.00	35.2	46.1	34.2	45.6	−2.9	−1.1
S_1	2457	0.25	0.30	1.00	0.20	0.17	0.62	0.81	44.2	65.2	46.8	64.8	5.9	−0.6
S_2	2302	0.42	0.50	1.00	0.20	0.17	0.62	0.81	25.6	35.9	25.2	35.0	−1.6	−2.4
S_3	2338	0.38	0.45	1.00	0.20	0.17	0.62	0.81	29.2	41.5	28.8	40.0	−1.4	−3.6
S_4	2439	0.21	0.30	1.00	0.40	0.29	0.56	0.73	49.2	70.2	51.7	73.2	5.1	4.3
S_5	2223	0.43	0.60	1.00	0.40	0.29	0.56	0.73	23.1	30.2	22.3	31.8	−3.7	5.3
S_6	2322	0.32	0.45	1.00	0.40	0.29	0.56	0.73	32.5	46.2	32.1	45.6	−1.3	−1.3
S_7	2324	0.25	0.40	1.00	0.60	0.38	0.54	0.69	38.9	59.1	40.5	58.4	4.0	−1.1
S_8	2192	0.38	0.60	1.00	0.60	0.38	0.54	0.69	25.1	34.9	24.6	35.7	−2.1	2.4
S_9	2223	0.34	0.55	1.00	0.60	0.38	0.54	0.69	28.1	42.2	27.5	39.9	−2.3	−5.5
S_{10}	2440	0.24	0.30	1.20	0.20	0.19	0.60	0.79	44.6	69.4	47.8	66.5	7.2	−4.1
S_{11}	2288	0.40	0.50	1.20	0.20	0.19	0.60	0.79	24.6	36.4	25.8	36.1	4.9	−0.9
S_{12}	2323	0.36	0.45	1.20	0.20	0.19	0.60	0.79	28.6	43.1	29.5	41.2	3.1	−4.5
S_{13}	2431	0.20	0.30	1.20	0.40	0.32	0.55	0.71	55.1	71.0	53.6	76.4	−2.7	7.6
S_{14}	2220	0.41	0.60	1.20	0.40	0.32	0.55	0.71	24.8	35.1	23.2	33.4	−6.5	−4.9
S_{15}	2318	0.30	0.45	1.20	0.40	0.32	0.55	0.71	34.2	45.6	33.3	47.7	−2.6	4.7
S_{16}	2323	0.23	0.40	1.20	0.60	0.42	0.53	0.68	46.1	59.1	42.5	61.9	−7.8	4.7
S_{17}	2194	0.35	0.60	1.20	0.60	0.42	0.53	0.68	28.2	39.5	25.9	38.1	−8.0	−3.7
S_{18}	2224	0.32	0.55	1.20	0.60	0.42	0.53	0.68	29.4	44.6	28.9	42.4	−1.5	−5.0
S_{19}	2447	0.23	0.30	1.60	0.20	0.24	0.58	0.75	48.3	62.9	49.8	69.9	3.1	11.2
S_{20}	2297	0.38	0.50	1.60	0.20	0.24	0.58	0.75	24.9	36.2	27.0	38.1	8.4	5.3
S_{21}	2332	0.34	0.45	1.60	0.20	0.24	0.58	0.75	32.6	45.9	30.8	43.4	−5.5	−5.4
S_{22}	2341	0.24	0.40	1.60	0.40	0.39	0.53	0.69	37.9	62.7	41.1	59.6	8.6	−5.0
S_{23}	2213	0.37	0.60	1.60	0.40	0.39	0.53	0.69	23.1	37.5	25.0	36.5	8.4	−2.6
S_{24}	2243	0.34	0.55	1.60	0.40	0.39	0.53	0.69	30.0	42.1	28.0	40.7	−6.8	−3.3
S_{25}	2323	0.20	0.40	1.60	0.60	0.49	0.51	0.66	44.9	65.9	46.5	68.7	3.6	4.2
S_{26}	2148	0.36	0.70	1.60	0.60	0.49	0.51	0.66	24.9	34.1	23.5	35.1	−5.7	3.0
S_{27}	2229	0.28	0.55	1.60	0.60	0.49	0.51	0.66	30.7	49.2	31.9	47.3	3.8	−3.8

FCD = Fresh concrete density, wb = water–binder ratio, wc = water–cement ratio, m = fly ash addition factor, p = FF = fly ash fraction in binder = $(m * p_s * s)/[1 + m * p_s * s]$, s = proportion of sand, p_s = sand replacement level, wb = water–binder ratio, A = 14.42, 19.23 at 7 and 28 day, respectively, %Difference = $100 * (f_{eqn} - f_{test})/f_{eqn}$ k at 7 day = $0.90 - 0.10 * \log_e(100 * p)$, k at 28 day = $1.2 - 0.14 * \log_e(100 * p)$; $f_{eqn} = A * \{([1 - p * (1 - k)]/wb) - 0.50\} = A * \{[(1 + m * p_s * s * k))/wc] - 0.50\}$.

6.3. Comparison of predicted and actual strength

Eq. (8) were utilised to compute the compressive strength of FAC mixes (S_1–S_{27}) with FA as SRM using the values of 'A' determined as mentioned earlier and the values of 'k' from Eq. (9a) (Table 2). It may be noted here that the value of 'p' in Eq. (9) relates to the fraction of FA in one unit of binder consisting of cement and FA.

Even though the actual difference (absolute values) between the strengths of CC Mix S_0 and FAC mixes, S_1 to S_{27}, is quite large,the computed difference between predicted values and actual strengths of these FAC mixes is only in the range of +11.2% to −8.0% which may be taken to be quite satisfactory (Table 3).

7. Applicability of strength prediction equation to concretes reported in literature

Most of the work reported on FA as replacement of sand, does not discuss explicitly the relationship between the concretes with and without FA as SRM. Often the concretes with FA as SRM had higher strength than the original control concrete (%Difference in Table 4a) and there was no attempt to maintain the strength levels in FACs same as that of CCs. However, from the information available in the literature on the contents of concretes, it is possible to estimate the strength of FAC mixes using the suggested strength prediction equation; this is done in Table 4b. The data indicate that there is a good agreement between strength values estimated by the equation and those reported by various authors. The value of 'k' was obtained from Table 2 in the absence of the data in this regard in the published literature, although it would have been preferable to use the experimentally determined value of 'k' in each case of fly ash. Despite this, the strength estimation technique suggested in this paper is found to be satisfactory as seen by values of %Difference in Table 4b.

8. Concluding remarks

(1) Fly ash (FA) can be used as a partial sand replacement material (SRM) in cement concretes. The 28 day compressive strength of Fly Ash Concrete can be estimated by the equation suggested in this paper. Cementing efficiency of fly ash, k, is a parameter used in this equation, which is based on modified Bolomey Equation.

(2) The prediction equation also considers the different levels of replacement of sand and also it is possible to account for cases when the quantity of FA added is more than that of sand replaced on weight basis.

(3) The prediction formula suggested can be used to modify any basic cement concrete mix so that the concretes with and without sand replacement by FA have similar strength.

Table 4a
Test results from published literature

S. no.	Author	Contents of concrete, kg/m^3						% SRL p_s	$P = F/(C+F)$	$wb = W/(C+F)$	f_c, MPa			
		C	F	S	CA	W	SP				7 day	28 day	56 day	90 day
1	Rafat Siddique (2002)	390	0	560	1170	185	2.6	0	0	0.474	19.4	26.4	29	31
		390	50	510	1170	187	3.5	10	0.114	0.425	21.4	28.2	31.2	34.2
		390	110	450	1170	190	3.6	20	0.22	0.38	22.6	30.8	34	38
		390	170	390	1170	190	3.7	30	0.304	0.339	25	34.9	40.2	44
		390	220	340	1170	192	3.7	40	0.361	0.315	26.5	38.9	44.6	49.8
		390	280	280	1170	195	3.9	50	0.418	0.291	27.2	40	46.3	51.4
2	Dhir RK, McCarthy, Title PAJ (2000)	350	0	700	1170	185	0	0	0	0.529		45		47
		350	35	665	1170	185	0	5	0.091	0.481		47		53
		350	70	630	1170	185	0	10	0.167	0.44		49		55
		350	105	595	1170	185	0	15	0.231	0.407		52		60
3	Mangaraj and Krishnamoorthy (1994)	1	0.00	1.86	3.3	0.6	0	0	0.00	0.60		20		
		1	0.09	1.77	3.3	0.6	0	5	0.09	0.55		22		
		1	0.19	1.67	3.3	0.6	0	10	0.16	0.51		23		
		1	0.28	1.58	3.3	0.6	0	15	0.22	0.47		23.5		
		1	0.37	1.49	3.3	0.6	0	20	0.27	0.44		23		
		1	0.47	1.40	3.3	0.6	0	25	0.32	0.41		29		

SP = superplasticiser, m = fly ash addition factor, p_s = replacement level, C = cement, F = fly ash, S = sand, CA = coarse aggregate, W = water, f_c = compressive strength.

Table 4b
Applicability of suggested estimation formula to some published literature

S. no.	Author	FAF m	% SRL p_s	p = FF = F/B	wb = W/B	'k' of fly ash		'A' of Bolomey equation		f_{test}, MPa from test		f_{eqn}, MPa from prediction equation		%Difference	
						7 day	28 day	7 day	28 day	7 day	28 day	7 day	28 day	7 day	28 day
1	Rafat Siddique (2002)	1	0	0.00	0.47			12.1	16.4	19.4	26.4	19.4	26.4	0.0	0.0
		1	10	0.11	0.43	0.66	0.86			21.2	29.8	21.4	28.2	0.8	−5.6
		1	20	0.22	0.38	0.59	0.77			22.8	32.7	22.6	30.8	−1.0	−6.3
		1	30	0.30	0.34	0.56	0.72			24.8	36.1	25.0	34.9	1.0	−3.4
		1	40	0.36	0.32	0.54	0.70			25.9	38.2	26.5	38.9	2.3	1.8
		1	50	0.42	0.29	0.53	0.68			27.2	40.6	27.2	40.0	0.0	−1.4
2	Dhir RK, McCarthy, Title PAJ (2000)	1	0	0.00	0.53				32.4		45.0		45.0		0.0
		1	5	0.09	0.48	0.68	0.89				50.4		47.0		−7.3
		1	10	0.17	0.44	0.62	0.81				55.0		49.0		−12.2
		1	15	0.23	0.41	0.59	0.76				58.9		52.0		13.3
3	Mangaraj and Krishnamoorthy (1994)	1	0	0.00	0.6				17.1		19.1		20.0		4.3
		1	5	0.09	0.55	0.68	0.89				21.3		22.0		3.0
		1	10	0.16	0.51	0.62	0.81				23.0		23.0		0.0
		1	15	0.22	0.47	0.59	0.77				24.9		23.5		−6.0
		1	20	0.27	0.44	0.57	0.74				26.4		27.0		2.1
		1	25	0.32	0.41	0.55	0.71				28.2		29.0		2.9

Note: %Difference = $100 * (f_{eqn} - f_{test})/f_{eqn}$.

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References

[1] Hewlett PC, editor, Lea's chemistry of cement and concrete. London: Arnold; 1998.
[2] Joshi RC, Lohtia RP. Fly ash in concrete: production, properties and uses. Netherlands: Gordon and Breach Science Publishers; 1999.
[3] Neville AM. Properties of concrete. London: Addison Wesley; 1996.
[4] Mehta PK, Monteiro PJM. Concrete: structure, properties, and materials. Chennai: Indian Concrete Institute; 1997.
[5] Ramachandran VS. Concrete admixtures handbook. New Jersey: No-Yes Publications; 2000.
[6] IS 456: 2000. Plain and reinforced concrete, Bureau of Indian Standards, New Delhi.
[7] Bolomey J. Granulation et prevision de la resistance probable des betons. Travaux 1935;19(30):228–32.
[8] Dhir RK, McCarthy MJ, Title PAJ. Use of conditioned PFA as a fine aggregate in concrete. Mater Struct 2000;33(225):38–42.
[9] Mangaraj BK, Krishnamoorthy S. Use of pond fly ash as part replacement for mortar and concrete. Indian Concrete J 1994(May): 279–82.
[10] Rafat Siddique. Effect of fine aggregate replacement with Class F fly ash on the mechanical properties of concrete. Cement Concrete Res 2003;33:539–47.
[11] Maslehuddin M. Effect of sand replacement on the early-age strength gain and long-term corrosion-resisting characteristics of fly ash concrete. ACI Mater J 1989;86(1):58–62.
[12] Berg E, Neal JA. Concrete masonry unit mix designs using municipal solid waste bottom ash. ACI Mater J 1998;95(4):470–9.
[13] Hwang KR, Noguchi T, Tomosawa F. Effects of fine aggregate replacement on the rheology, compressive strength and carbonation properties of fly ash and mortar, SP-178, ACI, 1998. p. 401–10.
[14] Bakoshi T, Kohno K, Kawasaki S, Yamaji N. Strength and durability of concrete using bottom ash as replacement for fine aggregate. SP-179, ACI, 1998; p. 159–72.
[15] Dattatreya JK, Rajamane NP, Neelamegam M, Annie Peter J, Gopalakrishnan S. Technical consideration for use of fly ash in structural concrete. New Build Mater Construct World 2002; October:56–71.
[16] Gopalakrishnan S, Rajamane NP, Dattatreya JK, Neelamegam M, Annie Peter J. Effect of partial replacement of cement with fly ash on the strength and durability of HPC. Indian Concrete J 2001; May:335–41.
[17] Rajamane NP. Making of concrete 'green' through use of fly ash. Green Business Opport. Confeder Indian Ind 2003;9(4):22–9.
[18] Brandt AM. Cement based composites: materials, properties and performance, E and FN SPON; 1995.
[19] De Larrard F. Concrete mixture proportioning: a scientific approach, E and F N Spon; 1999.
[20] Smith IA. Design of fly ash concrete. Proc Institution of Civil Eng, London, 1967;36:769–91.
[21] Ganesh Babu K, Sivanageswara Rao GS. Effect of fly ash in concrete. Cement Concrete Compos 1993;15:223–9.
[22] Hansen TC, Hedegaard SE. Modified rule of constant water content for constant consistency of fresh fly ash concrete mixes. Mater Struct 1992;25(150):342–54.