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Experimental Investigation on Viable Limit of Fly Ash Utilization in Concrete

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ABSTRACT

The knowledge about the utility of fly ash is well known worldwide. Moreover, even though fly ash is widely and abundantly available in India, its optimal utilization is not yet achieved. This paper attempts to give clarity on the viable limit of fly ash in structural concrete. The study confirms the applicability of efficiency factor method in the mix design and strength prediction of concrete. Maximum usable fly ash percentage depends upon the strength of concrete and type of chemical admixture.

Although the results presented herein may vary with change of constituent materials, type of concrete, type and power of concrete mixer, … etc., the trend in results would remain similar and will be useful for both researchers and practicing engineers in concrete technology domain striving for sustainable construction.

KEYWORDS: Cement, Compressive strength, Concrete, Efficiency factor, Fly ash, Workability.

INTRODUCTION

Research on fly ash and its utilization is being conducted for decades worldwide. Fly ash utilization in India is mainly influenced by the notifications of the Ministry of Environment, Forest and Climate Change, erstwhile Ministry of Environment and Forests (MoEF, 1999; 2003; 2009). However, in most of the major construction projects, use of ordinary Portland cement concrete (OPC) is still preferred to fly ash concrete. Moreover, there are differences among stakeholders for limiting its usage in concrete.

Fly ash is widely available in India. It is mostly of siliceous type and its properties are within the acceptable limits of Indian Standards for use in concrete (Murumi, 2017). IS 456 (BIS, 2000) specifies a maximum limit of 35% fly ash as cement replacement for computing maximum *w/cm* ratio and minimum cementitious material for a particular exposure condition of the structure. This maximum limit is also specified in IRC:112 (IRC, 2011) and MoRTH Specifications (IRC, 2013) for concrete road and bridge works. Although it has been clarified in the fourth amendment of IS 456 (BIS, 2013a) that fly ash percentage above 35% could be used in concrete, the excess should not be counted as cementitious. Maximum permissible fly ash limit in concrete is often perceived to be 35% of the total cementitious material in construction industry. A previous study by Basu and Saraswati (2006) also noted the existence of this misconception.

The unorganized construction industry in India is larger than the organized construction sector in terms of volume of concrete production. Fly ash is used in the form of fly ash-based Portland pozzolana cement in the unorganized sector. On the other hand, fly ash is externally admixed into concrete in the organized sector.

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Only some part of this sector, like building projects, is using fly ash, while the utilization level is relatively low or fly ash not at all used in bridge projects although there are certain exceptional cases. There are several reasons affecting the utilization of fly ash in concrete in India, which include concern on profit reduction, mindset of stakeholder, concern on the variability of fly ash quality and slower strength development, concern on maximum usable limit for fly ash percentage in concrete, concern on corrosion in fly ash concrete,… etc. (Murumi, 2017).

As regards mix design of fly ash concrete, Smith (1967) proposed "cementing efficiency" concept. Efficiency factor is that factor which makes the mass of a given fly ash "*f*" as equivalent to the mass of cement "*kf*" and it is used to make *w/(c+kf)* ratio instead of *w/c* ratio. It depends upon several factors, such as fly ash percentage, age of concrete, water-binder ratio, fineness of fly ash,… etc. Although attempting maximum fly ash utilization is helpful from various perspectives, there is always a limit to this (Munday et al., 1983; Gopalan and Haque, 1989; Ravina, 1997; Dinakar, 2012). However, there is no clear information and data on optimum fly ash usage limit for wide range of strength in the literature. In this research, it has been assumed that the efficiency factor is a function of fly ash percentage (Álvarez et al., 1988; Hobbs, 1988; Schiessl and Hardtl, 1991; Babu and Rao, 1993; 1994; 1996; Vissers, 1997; Bharatkumar et al., 2001; Pekmezci and Akyüz, 2004; Long et al., 2005; Khokhar et al., 2010; Cho and Jee, 2011; Cho et al., 2012). The efficiency factor is based upon compressive strength of concrete at 28 days of age. This paper presents clarity on the fly ash utilization limit in concrete based on expected strength of concrete through an experimental investigation on the design and utility level of fly ash in concrete.

Experimental Program

In the first part of the study, strength-based efficiency factor was estimated using mix design and strength data of past experiments conducted by the authors. Next, the optimized limit of fly ash was determined based on fresh concrete behaviour and cost aspects. The study was limited to siliceous fly ash (ASTM Class F) percentage from 15% up to 55% for conventional structural concrete with compressive strength ranging between 20 MPa and 60 MPa.

Materials Used

Cement

OPC 43 grade used in this study conformed to IS 8112 (BIS, 2013c). Chemical and physical properties are shown in Table 1. Blaine's fineness of cement was 290 m^2/kg and specific gravity was 3.15.

Table 1. Properties of cement

Sl. no.	Chemical properties	Test result
1	$(CaO - 0.7\ SO_3) \div (2.8\ SiO_2 + 1.2\ Al_2O_3 + 0.65\ Fe_2O_3)$	0.88
2	$Al_2O_3 \div Fe_2O_3$	1.43
3	Insoluble residue (% by mass)	1.94
4	Magnesia (% by mass)	0.95
5	Total sulphur content (% by mass)	1.80
6	Loss on ignition (% by mass)	1.82
7	Total chlorides (% by mass)	0.01
Sl. no.	**Physical properties**	**Test result**
1	Blaine's fineness (m^2/kg)	290
2	Soundness	
	(a) Le Chatelier expansion (mm)	1.0
	(b) Autoclave expansion (mm)	0.05
3	Compressive strength (MPa), 28 days	56.3

Fly Ash

Fly ash used was siliceous conforming to IS 3812 (Part 1) (BIS, 2013b), an equivalent of ASTM C618's Class F fly ash (ASTM Standard, 2015). Chemical and physical properties are shown in Table 2. Blaine's fineness was 343 m^2/kg and specific gravity was 2.10.

Table 2. Properties of fly ash

Sl. no.	Chemical properties	Test result
1	$SiO_2+Al_2O_3+Fe_2O_3$ (% by mass)	93.80
2	SiO_2 (% by mass)	62.40
3	Reactive silica (% by mass)	26.00
4	MgO (% by mass)	0.70
5	SO_3 (% by mass)	0.18
6	Na_2O (% by mass)	0.21
7	K_2O (% by mass)	1.20
8	Cl (% by mass)	0.03
9	CaO (% by mass)	1.90
10	Loss on ignition (% by mass)	1.30
Sl. no.	**Physical properties**	**Test result**
1	Blaine's fineness (m^2/kg)	343
2	Particle retention on 45 µm sieve, wet sieving (% by mass)	29
3	Lime reactivity (MPa)	5.1
4	Compressive strength of neat cement mortar at 28 days (% of plain cement mortar cubes)	90.3
5	Soundness by autoclave test (%)	0.08

Aggregates

Sand (natural sand) and coarse aggregates conformed to IS 383 (BIS, 1970). For coarse aggregates, two nominal maximum sizes of aggregates (m.s.a.) were used; namely 10 mm and 20 mm.

Cumulative percentages of sand passing 600 mm sieve and 300 mm sieve were 45% and 15%, respectively, which were within the range for Zone II sand of this standard. Specific gravities of sand, 10-mm aggregate and 20-mm aggregate were 2.64, 2.74 and 2.78, respectively. Coarse aggregates were angular in shape.

Water

Water used in the experiment for concrete mixing and curing was potable, sourced from municipal supply conforming to IS 456 (BIS, 2000).

Chemical Admixture

Two types of chemical admixtures (high-range water reducing admixture and low-range water reducing admixture) were used to maintain the required workability in concrete mixes. These were a polycarboxylate ether (PCE)-based superplasticizer and a modified lignosulfonate (MLS)-based superplasticizer, respectively, conforming to IS 9103 (BIS, 1999).

Specimen Preparation

Preparation of Aggregates

Coarse aggregates were first washed to remove deleterious materials and kept in water for 24 h. These were then dried with jute cloth to bring them to saturated-surface-dry (SSD) condition as per ASTM C127 (ASTM Standard, 2012a), while sand was treated as per ASTM C128 (ASTM Standard, 2012b). Moisture correction was carried out for sand for every batch of mix.

Batching of Materials

Water, cement, fly ash and aggregates were batched by mass on a weighing scale with an accuracy of ± 0.05 kg and chemical admixture was prepared to an accuracy of ± 0.01 g.

Concrete Mixing

Concrete mixes were prepared as per IS 516 (BIS, 1959a). A tilting drum-type mixer (0.1 m^3 capacity) was used to prepare the concrete. Aggregates were first dry-mixed for 30 seconds. Cement and fly ash were then added along with approximately 70% of the design water. After few minutes of mixing, chemical admixture was added to the remaining water and used in the mix. Chemical admixture was administered in such a manner that slump suitable for pumping concrete could be obtained.

Casting and Curing of Specimens

After testing fresh concrete properties (mixing time, slump and cohesion), concrete was immediately cast into steel moulds coated with oil. A vibrating table was used to vibrate the moulds for full compaction. After 24 h of casting, these were marked and cured in an open water tank until the testing day. The curing water temperature was under ambient condition. The concrete specimens were not allowed to become dry until tested.

Test Methods and Procedures

Fresh Properties

Minimum mixing time was kept at 2 minutes as per the specifications of IS 456 (BIS, 2000). The workability of concrete was tested using slump cone in accordance with the specifications of IS 1199 (BIS, 1959b). Cohesiveness of concrete was measured by visual assessment on the slumped concrete. The sides of the concrete were gently tapped with a tamping rod for five times. The five classes of cohesion as per Deshapriya (2003) are shown in Table 3. Finishability was visually estimated by passing a float over the concrete in the mould with an even pressure for ten times (Deshapriya, 2003). Table 4 shows different classes of finishability. The fourth class was introduced in this study for sticky mixes.

Table 3. Cohesion classes

Class	**Cohesion property (excluding collapse slump)**	
	Description	Behaviour of slumped concrete after gentle tapping for five times
1	Over-cohesive	Little further slump
2a	Very cohesive	Gradually slumps further, no shearing
2b	Cohesive	Gradually slumps further, some shearing
2c	Little cohesion	Gradually slumps further, then partial collapse
3	No cohesion	Slumped concrete shears

Table 4. Finishability classes

Class	**Finishability property**	
	Description	Appearance of concrete after ten passes with float
1	Very good finishability (little effort)	Smooth surface, few voids
2	Good finishability (moderate effort)	Smooth surface, some voids
3	Unacceptable finishability (difficult to finish)	Uneven surface, exposed aggregate
4	Sticky finishability (difficult to finish)	Smooth surface, glassy look

Hardened Concrete Property

Compressive strengths were measured on 150 mm cubes at 7 days and 28 days. The test was conducted using a compression testing machine of 250 t capacity as per IS 516 (BIS, 1959a).

Estimating Compressive Strength of Concrete

OPC Concrete

Experiments were conducted on OPC concrete (control) mixes for different *w/c* ratios covering a wide range of strength. The *w/c* ratio varied from 0.30 through 0.60. Figure 1 shows the trendline of compressive strength relationship with *w/c* ratio for control mixes at 28 days (110 mix design data).

Trendline equations for this relationship at 7 days and 28 days are represented by the formulae indicated by Eq. 1 and Eq. 2, respectively, as shown below:

$$C_7 = 137.60e^{-3.42(w/c)} \text{ for 7 d } (R^2 = 0.85) \qquad (1)$$

$$C_{28} = 154.80e^{-3.07(w/c)} \text{ for 28 d } (R^2 = 0.92) \qquad (2)$$

The trendline can be represented in different mathematical expressions and the coefficients in the equation will change with variation in data. These results had a trend with the results of Kaplan (1960) who experimented on a wide range of *w/c* ratios ranging from high strength to low strength. Strength results of researchers who reported from different countries are also shown. The data was of Kaplan (1960); Álvarez et al. (1988); Ravina and Mehta (1988); Gopalan and Haque (1989); Hansen (1990); Hedegaard and Hansen (1992); Bharatkumar et al. (2001); Bouzoubaâ and Lachemi (2001); Han et al. (2003); Lee et al. (2003); Durán-Herrera et al. (2011); Huang et al. (2013); and Shaikh and Supit (2015). The OPC trendline of the present experiments is similar to the combined data of these researchers. Compressive strength therefore decreases with increase in *w/c* ratio (Abrams, 1919).

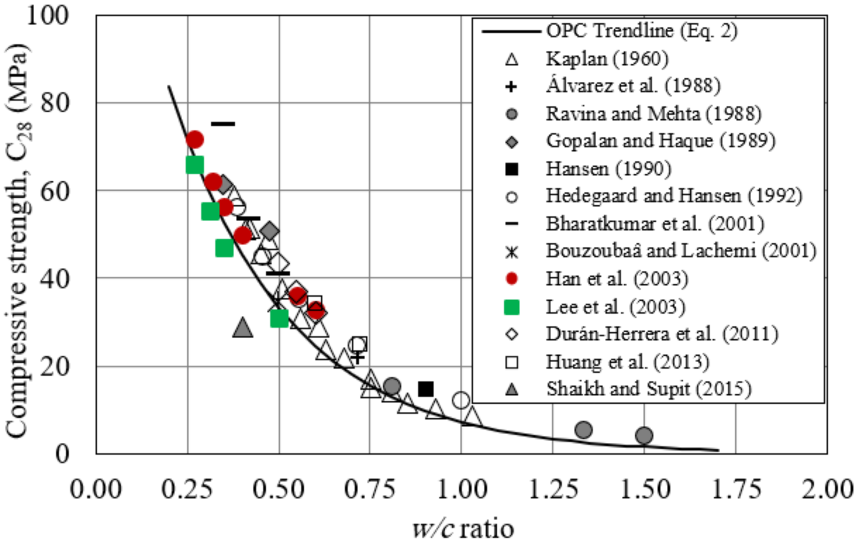

Figure (1): Compressive strength *vs.* *w/c* ratio for OPC concrete

Fly Ash Concrete

Efficiency factor of fly ash is defined in such a way that the strength of fly ash concrete can be predicted using the strength-*w/c* ratio relationship of OPC concrete. One can compare fly ash concrete with its counterpart OPC concrete in terms of various criteria (e.g. compressive strength). When fly ash is used, all parts of fly ash cannot act as cement for providing strength. Efficiency factor of fly ash is therefore used to match the effective binder content with that of cement content. This part of experimental study validates efficiency factor concept by using a wide range of *w/b* ratio (0.30-0.60) and fly ash (FA) percentage (15%, 25%, 35%, 45% and 55%). The 7-day and 28-day efficiency factors of fly ash are represented by Eq. 3 and Eq. 4, respectively.

$$k_7 = 0.13F^{-0.75} \quad (3)$$

$$k_{28} = 0.20F^{-0.75} \quad (4)$$

The efficiency factor of fly ash decreases upon increase in fly ash percentage. Eq. 3 and Eq. 4 were used to compute *w/b* ratio for 7-day and 28-day strength of fly ash concrete (120 mix design data), respectively. The compressive strength values were then compared with those of OPC concrete at 7 days and 28 days represented by Eq. 1 and Eq. 2, respectively (Figure 2).

Some data marked in 35%, 45% and 55% fly ash cases for low *w/b* ratio shown here isn't cost-effective or practically workable. Some mixes were highly cohesive and took excessive mixing time, while in some other cases, the admixture dosage was high, making the cost of concrete high, but these admixtures could be cast in the laboratory and hence reported. All data points are in close proximity to the OPC trendline.

The present experimental results are also compared with the data of other researchers reported in the literature (Figure 2). The data is of Álvarez et al. (1988); Ravina and Mehta (1988); Gopalan and Haque (1989); Hansen (1990); Hedegaard and Hansen (1992); Bharatkumar et al. (2001); Bouzoubaâ and Lachemi (2001); Han et al. (2003); Lee et al. (2003); Sukumar et al. (2008); Durán-Herrera et al. (2011); Huang et al. (2013); and Shaikh and Supit (2015). In this figure, the efficiency factor represented by Eq. 4 has been utilized to compute effective binder.

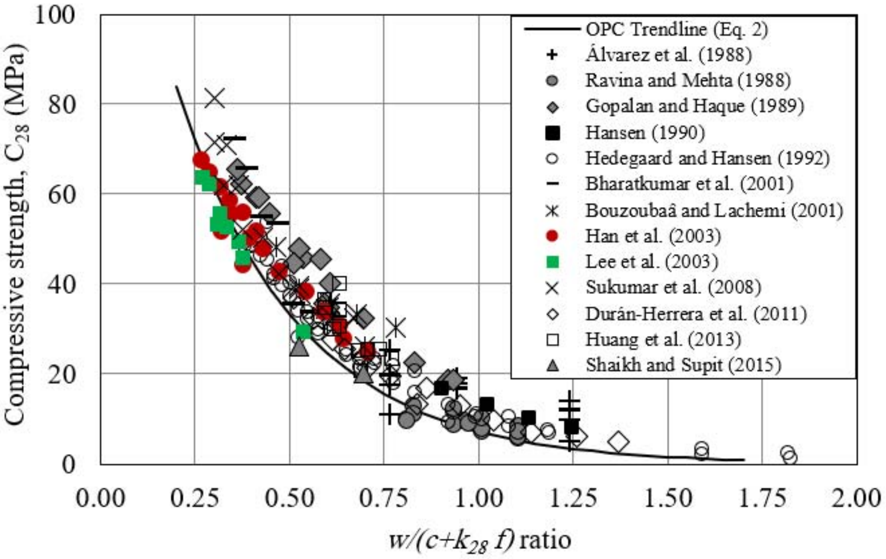

Figure (2): Compressive strength *vs.* *w/b* ratio for fly ash concrete

The present strength results for both OPC concrete and fly ash concrete have a lower bound as compared to that reported by other researchers. The efficiency factor values of fly ash reported by other researchers shown here appear to be higher than that of fly ash used in this study. This clearly shows that as reported elsewhere (Murumi and Gupta, 2015), the efficiency factor concept is applicable for a wide range of strength and fly ash percentage.

Optimization of Concrete Mix Using Fly Ash

Procedure of Study

In order to achieve reasonable cost of concrete with fly ash, mix optimization was carried out in the next phase of experiment with four *w/b* ratios; namely, 0.31, 0.39, 0.47 and 0.55 which correspond to M 50, M 35, M 30 and M 20 grades of concrete, respectively. The ratio of 10-mm to 20-mm coarse aggregate was 40:60 by weight for maximum packing density. The *s/a* ratio for different water to powder ratios was used based on the authors' experience; the values were in between the range suggested by Marsh (1997) and IS 10262 (BIS, 2009).

A minimum amount of powder is required to make a workable mix depending on the grade of concrete. Besides cement, this powder content can be obtained from any fine materials like fly ash and ground granulated blast furnace slag (GGBS) which are pozzolanic. Inert powder materials (e.g. marble powder and granite powder) can also be used in concrete without affecting strength if proper moisture correction is carried out and the chemical admixture dosage is better represented as percentage of total powder content (Anuj, 2015). A number of trial mixes were initially prepared to determine the appropriate water content and chemical admixture content required to achieve a target slump of 100-150 mm for pumping concrete. Mix optimization procedure is explained as follows:

- For a given *w/b* ratio and fly ash percentage, different values of water content (at least three) were assumed and the mix design was carried out. Chemical admixture was administered as a single dose in the final mix.
- Workability defined by mixing time, slump, type of slump, cohesion class (Table 3) and finishability class (Table 4) was then measured on fresh concrete.
- The cost of materials was based on the prevailing market rate around New Delhi during 2015-2016. It includes transportation cost. Cost considered (in INR) was 0.10/kg for water; 5.40/kg for cement; 0.90/kg for fly ash; 1.00/kg for sand; 0.95/kg for coarse aggregates; 110.00/kg for PCE-based admixture and 30.00/kg for MLS-based admixture.
- Out of the three different mixes, the best possible mix was then chosen based on the combined effect of workability, admixture demand and cost of concrete.

Table 5 and Table 6 show the mix proportioning details for best possible PCE-based and MLS-based mixes, respectively. Remarks on fresh concrete properties are also presented for each mix type. This includes mixing time of concrete, slump, type of slump, cohesion and finishability of concrete. Beyond a certain higher fly ash percentage, collapse slump occurred. A typical example herein describes the process of selecting the best mixes for a given *w/b* ratio (or strength range). Suppose that mixes nos. P1a, P1 and P1b represented 0% fly ash case with *w/c* ratio of 0.31 and water content of 135, 145 and 155 kg/m^3, respectively. The corresponding cement contents were 435, 468 and 500 kg/m^3; admixture dosages were 1.15%, 0.9% and 0.7% by weight of cement and mixing times were 5.0, 4.5 and 3.5 minutes, while costs of concrete (in INR) were 4776.45, 4810.47 and 4854.25, respectively. Mix no. P1a gave a shear slump with "class 2c" cohesion and was the cheapest of the three. The paste content then became better for mix no. P1 that gave true slump and "class 2b" cohesion. Mix no. P1b produced further better paste with true slump and "class 2a" cohesion as well as better finishability (class 1), but cost was the highest and hence mix no. P1 was considered the best mix as shown in Table 5.

RESULTS

Admixture Demand

Admixture quantity other than that required for design slump resulted in too low or too high slump. Admixture dosage was taken as the percentage of total weight of cementitious materials; that is, percentage by weight of cement plus fly ash.

Table 5. Mix design and other particulars of best PCE-based mixes

w/b ratio	Mix no.	*F*	Weight of materials (kg/m^3)						Mix time (min)	Slump (mm)	Type of slump	Cohesion class	Finishability class
			w	*c*	*f*	*s*	CA	Admix.					
0.31	P1	0%	145	468	0	745	1118	4.21	4.5	130	True	Class 2b	Class 2
	P2	15%	145	408	72	724	1097	3.84	4.5	120	True	Class 2a	Class 1
	P3	20%	155	428	107	686	1046	4.28	6.0	200	Collapse	Class 1	Class 4
	P4	25%	165	448	149	643	990	5.08	7.5	230	Collapse	Class 1	Class 4
0.39	P5	0%	160	410	0	770	1101	1.85	3.0	110	True	Class 2b	Class 2
	P6	15%	160	358	63	753	1081	1.68	3.0	110	True	Class 2b	Class 2
	P7	25%	170	367	122	700	1024	2.20	3.5	110	True	Class 2b	Class 1
	P8	35%	170	352	190	659	990	3.80	5.0	250	Collapse	Class 1	Class 4
0.47	P9	0%	165	351	0	810	1097	1.05	2.0	120	True	Class 2b	Class 2
	P10	15%	165	306	54	794	1082	1.08	2.0	105	True	Class 2b	Class 1
	P11	25%	165	295	98	762	1066	1.18	3.0	120	True	Class 2a	Class 1
	P12	35%	165	284	153	726	1043	1.97	4.0	110	True	Class 2a	Class 1
	P13	45%	175	287	235	660	974	2.61	5.5	195	Collapse	Class 1	Class 4
0.55	P14	0%	175	318	0	836	1071	0.64	2.0	100	True	Class 2b	Class 2
	P15	15%	175	278	49	819	1060	0.65	2.0	100	True	Class 2b	Class 2
	P16	25%	175	268	89	788	1048	0.71	2.0	130	True	Class 2b	Class 1
	P17	35%	165	243	131	771	1061	1.31	3.0	135	True	Class 2a	Class 1
	P18	45%	165	231	189	730	1037	1.56	4.5	130	True	Class 2a	Class 1
	P19	50%	165	224	224	707	1020	2.24	5.0	200	Collapse	Class 2a	Class 1
	P20	55%	175	230	281	657	965	2.81	6.0	220	Collapse	Class 1	Class 1

Table 6. Mix design and other particulars of best MLS-based mixes

w/b ratio	Mix no.	*F*	Weight of materials (kg/m^3)						Mix time (min)	Slump (mm)	Type of slump	Cohesion class	Finishability class
			w	*c*	*f*	*s*	CA	Admix.					
0.39	M1	0%	160	410	0	770	1101	7.59	3.5	100	True	Class 2b	Class 2
	M2	15%	160	358	63	753	1081	7.16	3.5	110	True	Class 2b	Class 2
	M3	25%	170	367	122	700	1024	10.27	7.0	90	True	Class 2a	Class 1
0.47	M4	0%	165	351	0	810	1097	3.86	3.0	100	True	Class 2b	Class 2
	M5	15%	165	306	54	794	1082	3.60	3.0	100	True	Class 2b	Class 1
	M6	25%	165	295	98	763	1065	7.09	4.0	110	True	Class 2a	Class 1
	M7	35%	175	301	162	704	1011	9.73	8.0	110	True	Class 2a	Class 1
0.55	M8	0%	175	318	0	836	1071	1.75	2.0	130	True	Class 2b	Class 2
	M9	15%	175	278	49	819	1060	1.63	2.0	130	True	Class 2b	Class 2
	M10	25%	165	252	84	805	1078	3.37	2.5	130	True	Class 2b	Class 2
	M11	35%	165	243	131	771	1061	4.85	3.5	120	True	Class 2a	Class 1
	M12	45%	175	245	201	707	1006	8.47	5.0	110	True	Class 1	Class 1

Legend:

F- fly ash percentage; *w*- water; *c*- cement; *f*- fly ash; *s*- sand (fine aggregate); CA- coarse aggregate; Admix.- chemical admixture.

Figure 3 presents the summary admixture content (weight per cubic meter of concrete) for the best mixes. Admixture demand in MLS-based mixes was much higher compared with PCE-based mixes. Admixture demand of the mix was dependent upon fly ash percentage and *w/b* ratio. For a fixed *w/b* ratio, admixture demand increased with increasing fly ash percentage. Admixture dosage beyond 1% (in PCE-based) and 2% (in MLS-based) mixes retarded the setting time of concrete by over 30 h from the time of casting.

Workability and Mixing Time

Workability improved with addition of fly ash, but at high fly ash percentage, PCE-based mixes produced collapse slump and MLS-based mixes produced low slump. For a fixed strength range and slump, mixing time increases for high fly ash percentage. Mixing time of MLS-based mixes is relatively higher than that of PCE-based mixes.

Powder Content, Cost of Concrete and Optimum Fly Ash Percentage

Cement content decreased with increasing fly ash percentage up to a certain limit and increased for all *w/b* ratios. There was a maximum limit of fly ash percentage for a particular strength range. Although there was cohesiveness in MLS-based mixes with higher fly ash percentage, there were no consistency and plasticity. High fly ash percentage mixes required high admixture dosage, resulting in excessive retardation of setting time. Cost of OPC concrete was higher. Cost of fly ash concrete decreased with increasing fly ash percentage till a point after which it began to increase due to higher admixture demand. Figure 4 presents the cost of concrete *vs.* fly ash percentage relationship for best mixes made of PCE-based and MLS-based admixtures. There was a certain fly ash percentage up to which the cost of concrete made of PCE-based and MLS-based mixes gave similar cost. Beyond these points, PCE-based mixes were more effective for better workability and cost reduction.

Three optimum fly ash percentage levels were identified; namely, cost optimized (OPT), lower optimized (OPT 1) and upper optimized (OPT 2) fly ash percentage. OPT corresponds to minimum cost of concrete; OPT 1 is a lower fly ash percentage usable without much increase in cost; and OPT 2 represents maximum possible fly ash percentage that can be cast conveniently. Fly ash percentage above OPT 2 level produced excessive stickiness. Cost-optimized fly ash percentage was computed by differentiating the second order polynomial equations obtained from Figure 4.

Figure 5 presents the range of potential fly ash percentage (OPT and OPT 2 limits) for different strength levels of concrete (PCE-based mixes) along with typical data of other researchers. The data of Munday et al. (1983) is similar to the OPT 2 limits. Sukumar (2008) used materials with Blaine's fineness of 336 m^2/kg (OPC 53) and 428 m^2/kg (fly ash) for self-compacting concrete (SCC), while those of Dinakar (2012) were 370 m^2/kg (OPC 53) and 400 m^2/kg (fly ash) for both normal concrete and SCC. These fineness values are higher than in the present study (290 m^2/kg for OPC 43 and 343 m^2/kg for fly ash). Apart from superplasticizer, they also used viscosity-modifying admixture. Hedegaard and Hansen (1992), Durán-Herrera et al. (2011) and Meera et al. (2015) (who used non-optimized mixes but could be cast in the laboratory) did not use viscosity-modifying admixture. Higher volume of fly ash concrete can therefore be used in low-strength range as compared to high-strength range.

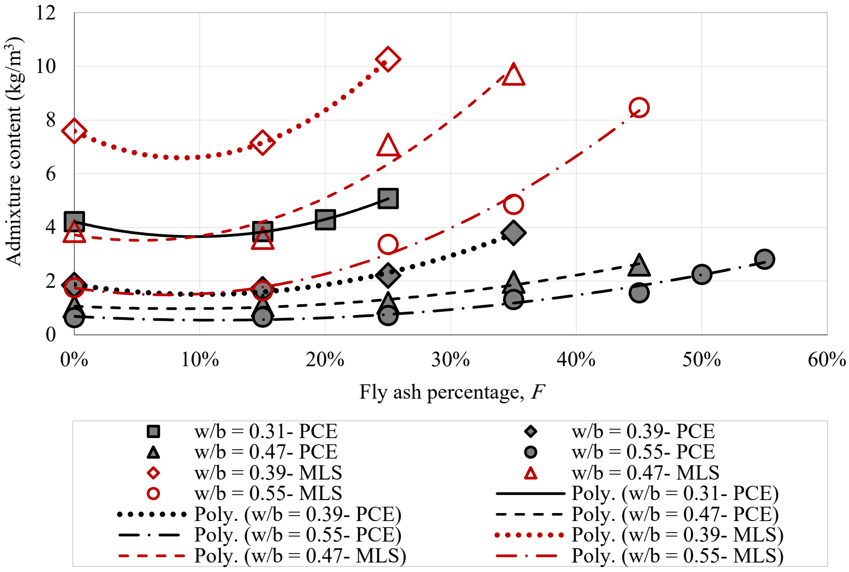

Figure (3): Variation in admixture content with fly ash percentage

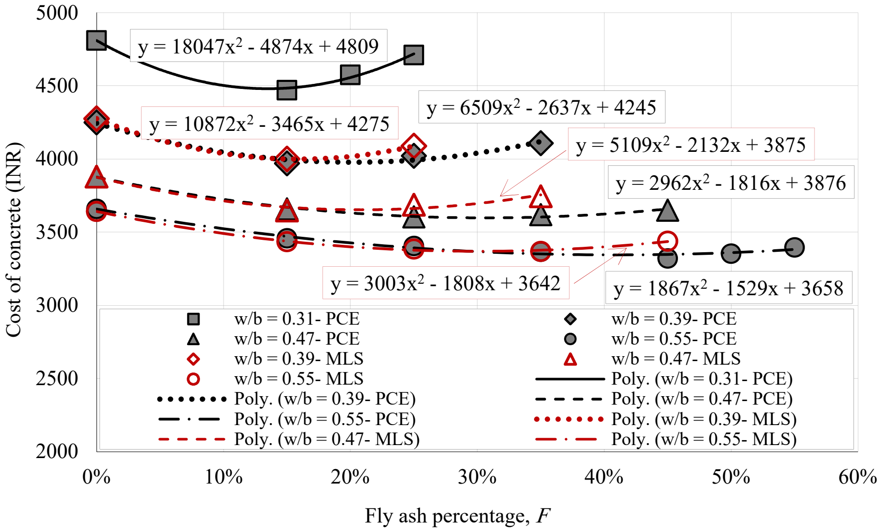

Figure (4): Variation in cost of concrete with fly ash percentage

Limiting cases of powder content for PCE-based and MLS-based mixes are shown in Figure 6 and Figure 7, respectively. Corresponding fly ash percentage is shown in brackets alongside powder content. There is a significant saving in cement by adopting OPT and OPT 2 mixes. Minimum powder content for a good workable mix depends on the strength level. Lower-strength concretes showed harsher mix as compared to higher-strength concretes due to lower powder content.

In PCE-based mixes, concrete was very sticky at high fly ash percentage, irrespective of admixture dosage, but it showed high deformability and no segregation as reported by Takada (2004). Viability of higher fly ash utilization was more in PCE-based mixes as compared to MLS-based mixes.

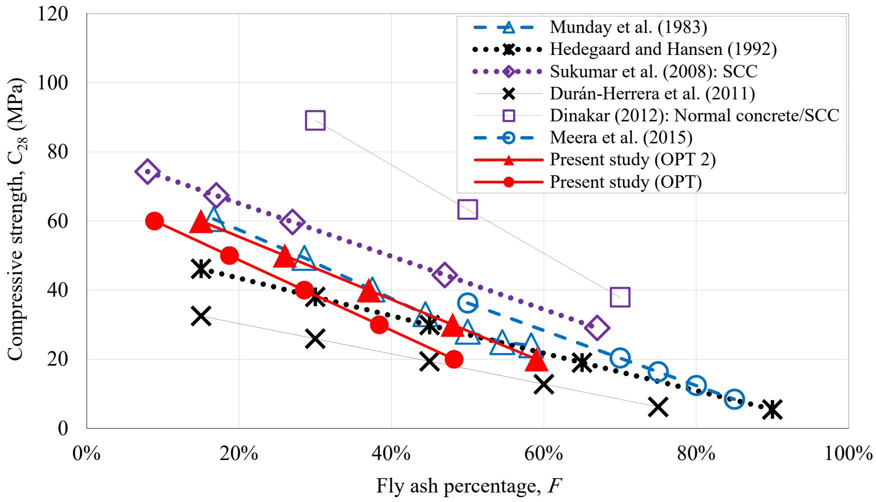

Figure (5): Utility level of fly ash percentage in concrete

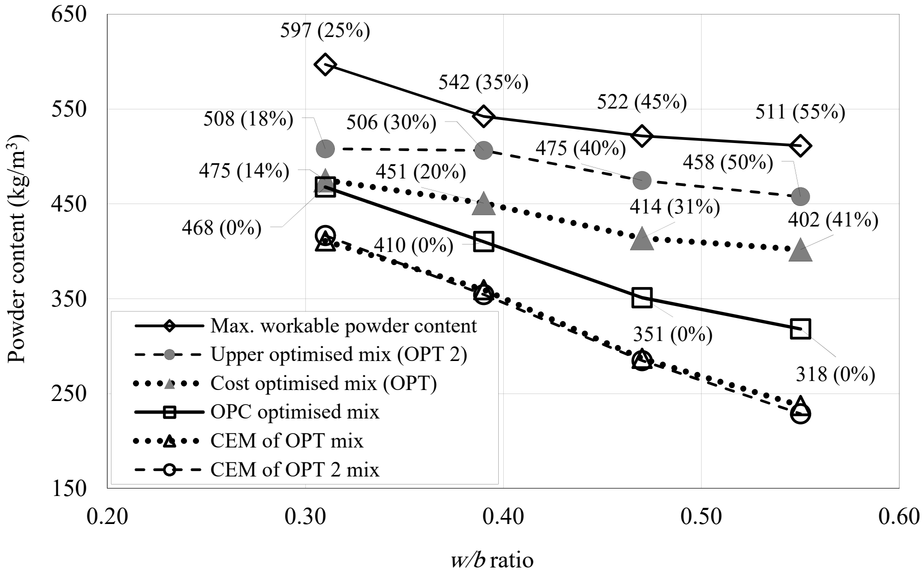

Figure (6): Variation in powder content for PCE-based mixes

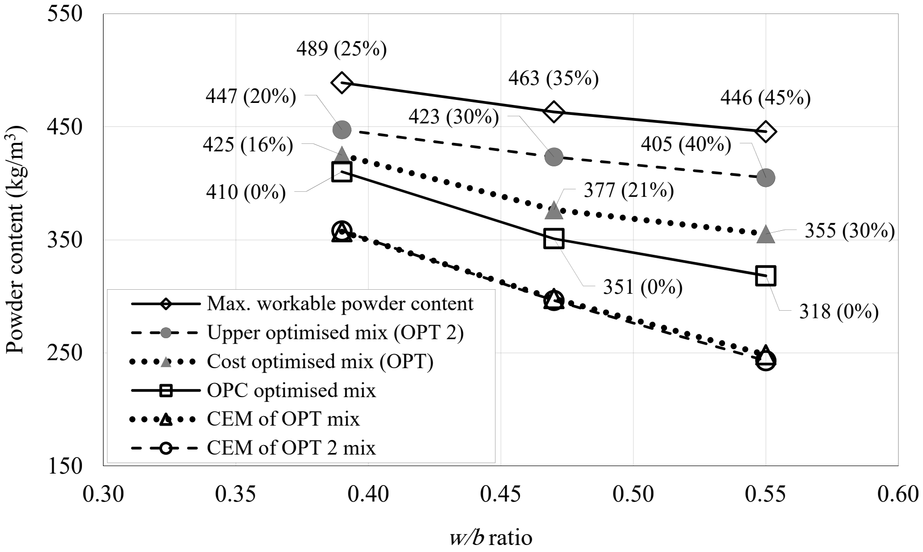

Figure (7): Variation in powder content for MLS-based mixes

Aggregate Saving

The aggregate quantity decreased with increasing fly ash percentage. There was a relatively higher aggregate saving in lower-strength concretes due to higher amount of fly ash. For a fixed fly ash percentage and *w/b* ratio, the type of chemical admixture did not have significant effect on the saving in total aggregate.

CONCLUSIONS

It is imperative to understand why and how fly ash should be used in concrete for a sustainable construction. Fly ash usage up to its optimum level is beneficial, leading to reduction of cement and aggregate consumption, enhanced workability and reduced cost of concrete. Based on the results, it has been concluded that:

- Efficiency factor concept is useful for designing fly ash concrete and predicting its compressive strength.
- Potential utilization of higher fly ash percentage increases with decreasing strength level of concrete.
- Viability of utilization of higher fly ash percentage decreases with decrease in water-reducing potential of chemical admixture.

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REFERENCES

Abrams, D.A. (1919). "Design of concrete mixtures". Bulletin No. 1, Structural Materials Research Laboratory, Lewis Institute. Chicago, Illinois, USA.

Álvarez, M., Salas, J., and Veras, J. (1988). "Properties of concrete made with fly ash". International Journal of Cement Composites and Lightweight Concrete, 10 (2), 109-120.

Anuj. (2015). "Utilization of marble and granite powders as green building materials in concrete". PhD Thesis. Indian Institute of Technology Delhi, New Delhi, India.

ASTM Standard. (2012a). "ASTM C127-12: Standard test method for density, relative density (specific gravity) and absorption of coarse aggregate". ASTM International, West Conshohocken, PA, USA.

ASTM Standard. (2012b). "ASTM C128-12 standard test method for density, relative density (specific gravity) and absorption of fine aggregate". ASTM International, West Conshohocken, PA, USA.

ASTM Standard. (2015). "ASTM C618-15: Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete". ASTM International, West Conshohocken, PA, USA.

Babu, K.G., and Rao, G.S.N. (1993). "Efficiency of fly ash in concrete". Cement and Concrete Composites, 15 (4), 223-229.

Babu, K.G., and Rao, G.S.N. (1994). "Early strength behaviour of fly ash concretes". Cement and Concrete Research, 24 (2), 277-284.

Babu, K.G., and Rao, G.S.N. (1996). "Efficiency of fly ash in concrete with age". Cement and Concrete Research, 26 (3), 465-474.

Basu, P.C., and Saraswati, S. (2006). "Are existing IS codes suitable for engineering of HVFAC?" The Indian Concrete Journal, 80 (8), 17-21.

Bharatkumar, B.H., Narayanan, R., Raghuprasad, B.K., and Ramachandramurthy, D.S. (2001). "Mix proportioning of high-performance concrete". Cement and Concrete Composites, 23 (1), 71-80.

Bouzoubaâ, N., and Lachemi, M. (2001). "Self-compacting concrete incorporating high volumes of class F fly ash: preliminary results". Cement and Concrete Research, 31 (3), 413-420.

Bureau of Indian Standards (BIS). (1959a). "IS 516: 1959 (reaffirmed 2004)- Methods of tests for strength of concrete (incorporating amendment nos. 1 & 2)". BIS, New Delhi, India.

Bureau of Indian Standards (BIS). (1959b). "IS 1199: 1959 (reaffirmed 2004)- Methods of sampling and analysis of concrete". BIS, New Delhi, India.

Bureau of Indian Standards (BIS). (1970). "IS 383: 1970 (reaffirmed 2002)- Specification for coarse and fine aggregates from natural sources for concrete (second revision)". BIS, New Delhi, India.

Bureau of Indian Standards (BIS). (1999). "IS 9103: 1999 (reaffirmed 2004)- Concrete admixtures: specification (first revision) (incorporating amendment nos. 1 & 2)". BIS, New Delhi, India.

Bureau of Indian Standards (BIS). (2000). "IS 456: 2000 (Reaffirmed 2005)- Plain and reinforced concrete: code of practice (fourth revision)". BIS, New Delhi, India.

Bureau of Indian Standards (BIS). (2009). "IS 10262: 2009- Concrete mix proportioning: guidelines (first revision)". BIS, New Delhi, India.

Bureau of Indian Standards (BIS). (2013a). "Amendment no. 4 to IS 456: 2000 (reaffirmed 2005)- Plain and reinforced concrete: code of practice (fourth revision), May 2013". BIS, New Delhi, India.

Bureau of Indian Standards (BIS). (2013b). "IS 3812 (part 1): 2013- Pulverized fuel ash: specification, part 1, For use as pozzolana in cement, cement mortar and concrete (third revision)". BIS, New Delhi, India.

Bureau of Indian Standards (BIS). (2013c). "IS 8112: 2013- ordinary Portland cement, 43 grade: specification (second revision)". BIS, New Delhi, India.

Cho, H.B., and Jee, N.Y. (2011). "Prediction model for cementing efficiency of fly ash concrete by statistical analysis". Advanced Materials Research, 250-253, 1293-1296.

Cho, H.B., Jee, N.Y., and Shin, N.Y. (2012). "Strength prediction of fly ash concrete using cementing efficiency by statistical analysis". Advanced Materials Research, 374-377, 1774-1777.

Deshapriya, M.A.A. (2003). "Role of cement content in determining resistance of concrete to reinforcement corrosion". PhD Thesis. University of Dundee, UK.

Dinakar, P. (2012). "Design of self-compacting concrete with fly ash". Magazine of Concrete Research, 64 (5), 401-409.

Durán-Herrera, A., Juárez, C.A., Valdez, P., and Bentz, D.P. (2011). "Evaluation of sustainable high-volume fly ash concretes". Cement and Concrete Composites, 33 (1), 39-45.

Gopalan, M.K., and Haque, M.N. (1989). "Mix design for optimal strength development of fly ash concrete". Cement and Concrete Research, 19 (4), 634-641.

Han, S.H., Kim, J.K., and Park. Y.D. (2003). "Prediction of compressive strength of fly ash concrete by new apparent activation energy function". Cement and Concrete Research, 33 (7), 965-971.

Hansen, T.C. (1990). "Long-term strength of high fly ash concretes". Cement and Concrete Research, 20 (2), 193-196.

Hedegaard, S.E., and Hansen, T.C. (1992). "Modified water/cement ratio law for compressive strength of fly ash concretes". Materials and Structures, 25 (5), 273-283.

Hobbs, D.W. (1988). "Portland-pulverized fuel ash concretes: water demand, 28-day strength, mix design and strength development". ICE Proceedings, 85 (2), 317-331.

Huang, C.H., Lin, S.K., Chang, C.S., and Chen, H.J. (2013). "Mix proportions and mechanical properties of concrete containing very high volume of Class F-fly ash". Construction and Building Materials, 46, 71-78.

Indian Roads Congress (IRC). (2011). "IRC:112-2011-Code of practice for concrete road bridges". IRC, New Delhi, India.

Indian Roads Congress (IRC). (2013). "Ministry of Road Transport and Highways-Specifications for road and bridge works (fifth revision)". IRC, New Delhi, India.

Kaplan, M.F. (1960). "The relation between ultrasonic pulse velocity and the compressive strength of concretes having the same workability but different mix proportions". Magazine of Concrete Research, 12 (34), 3-8.

Khokhar, M.I.A., Roziere, E., Turcry, P., Grondin, F., and Loukili, A. (2010). "Mix design of concrete with high content of mineral additions: Optimization to improve early age strength". Cement and Concrete Composites, 32 (5), 377-385.

Lee, H.K., Lee, K.M., and Kim, B.G. (2003). "Autogenous shrinkage of high-performance concrete containing fly ash". Magazine of Concrete Research, 55 (6), 507-515.

Long, G.Ch., Xie, Y.J., and Jiang, Z.W. (2005). "Efficiency of fly ash in cementitious materials". Advances in Cement Research, 17 (3), 113-119.

Marsh, B.K. (1997). "Design of normal concrete mixes". 2nd Ed. Building Research Establishment, Watford, UK.

Meera, M., Gidey, M.B., and Gupta, S. (2015). "Confirmation of efficiency factor in low strength range". In: Advancements in Structural Engineering: Materials, Design and Testing (Matsagar, V. (Ed.)). Bloomsbury Publishing India Pvt. Ltd., New Delhi, India, 5, 4221-4226.

Ministry of Environment and Forests (MoEF). (1999). "The Gazette of India". Extraordinary Part II, Section 3, Sub-Section (ii), Ministry of Environment and Forests, Notification No. S.O. 763(E), New Delhi, 14th Sept.

Ministry of Environment and Forests (MoEF). (2003). "Ministry of Environment and Forests, Notification No. S.O. 979(E)". New Delhi, 27th Aug. 2003.

Ministry of Environment and Forests (MoEF). (2009). "The Gazette of India". Extraordinary Part II, Section 3, Sub-Section (ii), Ministry of Environment and Forests, Notification No. S.O. 2804(E), New Delhi, 3rd Nov.

Munday, J.G.L., Ong, L.T., and Dhir, R.K. (1983). "Mix proportioning of concrete with PFA: a critical review". American Concrete Institute, SP 79-13, 267-288.

Murumi, K., and Gupta, S. (2015). “Evaluating the efficiency factor of fly ash for predicting compressive strength of fly ash concrete”. In: Advances in Structural Engineering: Materials (Matsagar, V. (Ed.)). Springer India, New Delhi, India, 3, 1747-1757.

Murumi, K. (2017). “Enhancing fly ash utilization in concrete”. PhD Thesis, Indian Institute of Technology Delhi, New Delhi, India.

Pekmezci, B.Y., and Akyüz, S. (2004). “Optimum usage of a natural pozzolan for the maximum compressive strength of concrete”. Cement and Concrete Research, 34 (12), 2175-2179.

Ravina, D., and Mehta, P.K. (1988). “Compressive strength of low-cement/high fly-ash concrete”. Cement and Concrete Research, 18 (4), 571-583.

Ravina, D. (1997). “Properties of fresh concrete incorporating a high volume of fly ash as partial fine sand replacement”. Materials and Structures, 30 (8), 473-479.

Schiessl, P., and Hardtl, R. (1991). “Efficiency of fly ash in concrete: evaluation of ibac test results, Technical Report”. Institut für Bauforschung, RWTH, Aachen, Germany, 1-31.

Shaikh, F.U.A., and Supit, S.W.M. (2015). “Compressive strength and durability properties of high-volume fly ash (HVFA) concretes containing ultrafine fly ash (UFFA)”. Construction and Building Materials, 82, 192-205.

Smith, I.A. (1967). “The design of fly-ash concretes”. Proceedings, Institution of Civil Engineers, 36 (4), 769-790.

Sukumar, B., Nagamani, K., and Raghavan, R.S. (2008). “Evaluation of strength at early ages of self-compacting concrete with high-volume fly ash”. Construction and Building Materials, 22 (7), 1394-1401.

Takada, K. (2004). “Influence of admixtures and mixing efficiency on the properties of self-compacting concrete”. PhD Thesis. Delft University of Technology, The Netherlands.

Vissers, L.J.L. (1997). “Fly ash as binder in concrete”. In: Studies in Environmental Science, Waste Materials in Construction: Putting Theory into Practice (Goumans, J.J.J.M., Senden, G.J. and van der Sloot, H.A. (Eds.)). Elsevier Science BV, Amsterdam, The Netherlands, 71, 279-288.