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Strength Development Characteristics Of High Strength Concrete Incorporating An Indian Fly Ash

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ABSTRACT: In the present investigation a humble effort has been made to finding the possibilities of an Indian fly ash in the production high strength high performance concrete and to evaluate the contributions of some significant mix composition parameters and age upon the strength development characteristics of concrete. A siliceous fly ash having a glass content of 34% and a fineness of 70% passing a 45 micron sieve was used. Experimentation has been performed over water-cementitious material ratios (w/cm) ranging from 0.27 to 0.42, cementitious material contents (cm) varying from 430 to 550 kg/m^3 and fly ash replacements ranging from 0 to 40% by weight of cementitious material. Compressive strengths of concrete have been evaluated at 7, 28 and 90 days age. Slump values of fresh concretes are in the range of 150-200 mm. Results of the present investigation indicate that compressive strength decreases as the w/cm and the fly ash replacement percentage increase at all the ages. 28 day strength of concrete has varied between 33 to 68 MPa while that of 90 day strength has ranged from 42 to 71 MPa. It is also revealed that a judicious use of fly ash has a tremendous potential in producing HSC. Based on statistical analysis of the database of the work, optimum fly ash replacements leading to strength similar to control (0% fly ash) have been determined as 10% and 17% for 28 and 90 days respectively. The results also suggest that HSC incorporating fly ash as a partial replacement of cement may be developed with a w/cm less than 0.34. Contribution of fly ash in improving strength of concrete increases with increasing replacement levels beyond 28 days. The average ratio of fly ash concrete strength between 7 and 28 days has been observed as 0.61 whereas gain in strengths from 28 to 90 days is about 20%.

Keywords: Aggregate, Admixture, Compressive strength, Fly ash, Fly ash replacement percentages, High strength concrete, Water-cementitious material ratio.

1. INTRODUCTION

The application of high strength concrete (HSC) has become very popular in India during the last few decades due to number of reasons-enhanced long term strength, high workability, better durability, economy and ecological factors. This tailor-made high performance concrete (HPC) has been successfully implemented in a number of high rise buildings, long span bridge projects in particular as well as in numerous structural applications like folded plates, domes etc. Concrete strength varying from 45 MPa to 60 MPa has been used in high rise buildings at Mumbai, Delhi and other metro cities. Vidya Sagar Setu at Kolkata where longest cable stayed bridge (in India) was built using high strength concrete. Concrete strength of 75 MPa is being used for the first time in India in J.J Flyover at Mumbai. A judicious use of supplementary cementitious materials (SCMs) and super-plasticizers (SPs) is responsible for production of high strength concrete. In addition, mix composition parameters like water-cementitious material ratio (w/cm) and cementitious material content have significant bearing on development of HSC. The SCMs most often used in the production of HSC are: fly ash, granulated blast furnace slag, metakaolin and micro silica. Amongst these pozzolanic materials, fly ash not only abundantly available in different parts of our country but also has the potential of being used in producing HSC. Despite the wide application of this waste material in a number of projects in India, high strength concrete incorporating fly ash is yet to develop confidence in construction sectors due to number of disadvantages-lack of simplified guideline for proportioning fly ash concretes, low early strength, wide variation in the physical and chemical characteristics of fly ash obtained from different thermal power plants in our country. Fly ash being a slow reacting pozzolan, when the primary cementitious material i.e. cement is replaced by equal weights of fly ash, the resultant concrete exhibits lower strength compared to the control/reference mix (0% fly ash) in the early ages. However at later ages, pozzolanic activity of fly ash becomes effective leading to considerable improvement in strength. Review of the existing literature in this direction has indicated that strength of fly ash concrete depends on a host of parameters like physical and chemical characteristics of cement and fly ash, water-binder ratio, total binder content, replacement percentage of fly ash, mix designing methods and the methods of curing. Reporting on the effects of these parameters upon strength development characteristics of fly ash based HSC is quite limited. In this direction a proper fundamental research work is still lacking. The present research work has been outlined with the aim of finding the possibilities of an Indian fly ash in the production of high strength concrete and to investigate the contribution of some of the mix composition parameters and age upon strength development characteristics of fly ash based HSC. A good quality siliceous fly ash with a Blaine's fineness of 340 m^2/kg and 70% passing a 45 micron sieve has been deliberately chosen for the investigation. Detailed experimental investigation involving a total of 16 concrete mixes, has been performed over a wide range of water-binder ratios, binder contents and fly ash replacement percentages. According to ACI, high strength concrete is defined as that over 6000 psi (i.e. 41 MPa) compressive strength adopted in 1984. It also has been mentioned that the value is not yet hard and fast and can vary depending on geographical locations. In the present investigation, 28 day Compressive strength of concretes targeted was between 40 to 60 MPa with slump values varying from 150 to 200 mm.

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2. MATERIALS FOR HIGH STRENGTH CONCRETE

The concrete ingredients used in the experimental work were tested to comply with the relevant Indian Standards. To assure uniformity of supply, the materials were subjected to periodical control tests. Physical and chemical characteristics of binder materials as determined in our laboratory and by Central Glass and Ceramic Research Institute, Kolkata and National Council for Cement and Building Material, Harayana are presented in Table 1.

2.1 Cement

In order to develop high strength concrete, use of high strength cement is recommended. Hence Ordinary Portland Cement having a 28 day compressive strength of 43 MPa (manufacturers name — Ultratech) complying with IS: 8112 – 1989 has been adopted in present investigation.

2.2 Fly Ash

A good quality siliceous fly ash conforming to IS: 3812 (2003) Part – I (mixtures of I and II fields from ESP) from Kolaghat Thermal Power Plant, West Bengal, India was used. Fly ash had a glass content of 34% and nearly 70% particles finer than 45 micron.

2.3 Fine aggregate

For the production of strong durable concrete, good quality sand should be used. Due to incorporation of fly ash, the volume of fines in the concrete will be high. Use of Zone II sand is proved to be beneficial with regard to workability. Due to scarcity of Zone II sand in this eastern part of India, natural clean river sand with a fineness modulus of 2.5 and conforming to Zone III as per IS: 383 was used. The specific gravity and water absorption values were obtained as 2.6 and 0.58% respectively.

2.4 Coarse aggregate

Though aggregates smaller than 12.5 mm is generally recommended for HSC, 20 mm coarse aggregates are the most commonly used aggregate for the variety of applications in construction works. Keeping this in view crushed, angular, graded coarse aggregate of nominal maximum size 20 mm has been adopted. Coarse aggregates were thoroughly cleaned with water to make free from dust and other impurities before being used in concrete making.

2.5 Chemical Admixture

A sulfonated melamine formaldehyde (SNF) based super-plasticizer; Conplast SP-430 (A FOSROC CHEMICAL INDIA PVT. LTD. product) was used to yield high workability for the concrete mixtures. The super-plasticizer used conforms to Type F as per ASTM C494. India lies in tropical climatic zone, where slump retention is a vital issue for better performance of HSC. The said super-plasticizer has already proved its worth for many advantages when it mixes with concrete like improved workability, slump retention, increased strength, improved quality, higher cohesion.

2.6 Water

Potable water was employed for the casting and curing of concrete.

Table 1: Physical and Chemical Characteristics of Cement and Fly Ash

Characteristics of Binder	43 Grade OPC Used	Fly Ash Used
Standard Consistency (%)	34	-
Fineness by		
a) Blaine's method (m^2/kg)	360	340
b) Percent retained on 45µ sieve by wet sieving (%)	15	30
c) BET surface area (m^2/kg)	1540	1460
Specific Gravity	3.15	2.13
Compressive Strength (MPa)		
a) 72 (+/-) 1 Hrs.	33.08	-
b) 168 (+/-) 2 Hrs.	41.28	-
c) 672 (+/-) 4 Hrs.	52.75	-
Table 1: Continued…		
Characteristics of Binder	43 Grade OPC Used	Fly Ash Used
Chemical analysis		
SiO_2 (%)	25.02	58.15
Al_2O_3 (%)	6.26	22.67
Fe_2O_3(%)	1.24	6.76
CaO (%)	61.82	1.23
MgO (%)	2.28	0.99
Na_2O (%)	0.31	0.21
K_2O (%)	0.44	2.33
TiO_2 (%)	0.14	1.56
Mineralogical analysis		
Glass phase (%)	-	34

3. EXPERIMENTAL PROCEDURE

The mix designing of high strength concrete is more thorough than that of an ordinary concrete. Particularly, the selection of mineral and chemical admixtures, mix compositions parameters like water-binder ratio, binder content should be very critical. According to existing reporting, the mix proportioning methods of HSC are mostly empirical and based on trial mixes. Though the Indian Standard "Recommended Guidelines for Concrete Mix Design" (IS: 10262 – 2009) has illustrated a typical example of mix designing of concrete using fly ash as partial replacement of OPC but a detail deliberation on the proportioning methodology is still lacking. The applicability of this standard is specifically meant for ordinary and standard grades of concrete only. After performing an extensive literature search in this direction with mix proportioning of fly ash based HSC, mix proportions of the present research work were formulated [1,2,4,6,8,16,17]. The experimental program included four sets of concrete mixtures in different combinations of w/cm and binder content viz. 0.3, 550 kg/m^3; 0.34, 510 kg/m^3; 0.38, 470 kg/m^3 and 0.42, 430 kg/m^3 respectively. Each set had mixtures at four fly ash replacement percentages - 0 (control mix), 20, 30 and 40% of the weight of binder. Hence a total number of 16 mixes were to be evaluated. All the concrete mixes were expected to develop a strength of 40 MPa or higher at 28 days age. For the present investigation the proportion of the coarse & fine aggregates

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was determined in the laboratory by trial & error so that the resultant aggregate mix yielded maximum packing density. This proportion has been kept constant for all the mixes. The binder contents, fly ash replacement percentages and water binder ratios have been prefixed to generate a wide database such that the effect of the most significant parameters i.e. w/cm, binder content and cement-fly ash ratio as inferred by Oluokun [9] on fly ash concrete strength can be evaluated in detail. The amount of coarse and fine aggregates used were 60% and 40 % by mass of total aggregates and the amounts of the different ingredients were determined by using the absolute volume formula [10]. Based on a large number of trials in laboratory, super-plasticizer dosage @ 2.0% by weight of binder was found to yield desired slump of concrete varying from 150 to 200 mm. This dosage has been kept constant in all the mixtures. Keeping in view, the water reducing effect of the fly ash in enhancing strength of concrete, 10% reduction in water content was considered while designing all the fly ash mixes. Thereafter only cement was replaced by fly ash (by equal weights). Due to change in the volumes of cement and fly ash necessary changes in the masses of the aggregates were calculated using the absolute volume method keeping all other mix proportion parameters constant [13,14,15]. Mix proportions of concrete mixtures are shown in Table 2. Cube specimens of 150 × 150 × 150 mm were used for compressive strength determination. All the specimens were moist cured under water for 28 days and then air cured in the laboratory. The specimens to be tested at 90 days age were immersed in water for 24 hrs before testing. Since the curing condition was uniform for all the specimens no adverse effect on the subsequent test results are expected due to temperature variations. Compressive strengths of concrete were determined at 7, 28 and 90 days. Each strength value was the average of five specimens. In all, a total of 240 specimens have been tested for compressive strength determination.

Table 2: Mix proportions

W/cm	Cement (Kg/m^3)	Fly Ash		Aggregates (Kg/m^3)		Water (Kg/m^3)	SP by weight of total binder (%)
		%	(Kg/m^3)	Fine	Coarse		
0.30	550	0	0	708	1062	165	2.0
0.27	440	20	110	709	1064	148.5	
	385	30	165	701	1052		
	330	40	220	693	1040		
0.34	510	0	0	713	1069	173.4	2.0
0.306	408	20	102	716	1074	156.06	
	357	30	153	709	1063		
	306	40	204	701	1052		
0.38	470	0	0	721	1081	178.6	2.0
0.342	376	20	94	726	1089	160.74	
	329	30	141	719	1079		
	282	40	188	712	1068		
0.42	430	0	0	732	1098	180.6	2.0
0.378	344	20	86	739	1108	162.54	
	301	30	129	732	1099		
	258	40	172	726	1089		

4. RESULTS AND DISCUSSIONS

4.1 General observation

Out of sixteen concrete mixes investigated, fourteen numbers of mixes have exhibited strength values equal to or greater than 40 MPa at 28 days thereby falling into the category of high strength concrete. The primary objective of the study was to develop high strength concrete incorporating fly ash. As per ACI, high strength concrete is defined as that over 40 MPa compressive strength. At 28 day age level, compressive strength of concrete has varied between about 33 to 68 MPa. The 90 day strength has observed to vary in the range of 42 to 71 MPa. In order to understand the contribution of fly ash on strength development of high strength concrete, a thorough analysis has been carried out and relevant discussions and the inferences drawn have been depicted in the following subsections. The variation in 28 and 90 day compressive strengths with respect to fly ash replacement percentages have been shown in Figure 1 and 2. In these figures, strength values at different w/cm ratios and binder contents have been plotted at each fly ash percentage. The relationships between strength and age of concrete are also shown in figure 3 to 6.

4.2 Effect of fly ash replacement percentage on the compressive strength of concrete

In the investigation, for fly ash concretes, w/cm ratios have been reduced by 10% with respect to control (0% fly ash). When the effect of fly ash replacement percentages on strength of concrete is considered, a distinctly decreasing trend has been noted as are shown in Figures 1 to 2. From the figures it is observed that for all the w/cm ratios and binder contents, strength of control concrete exhibits maximum values. With incorporation of fly ash as a partial replacement of cement on equal mass basis, there is a

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reduction in strength with increasing fly ash percentages yielding minimum values for 40% fly ash replacement. This is observed at both 28 and 90 days. Fly ash is a very slow reactive pozzolan and contribution of fly ash towards strength due to pozzolanic activity becomes significant from 28 days onwards. In this connection, it may be worthwhile to mention that the fly ash used in the investigation had low reactive silica content and fineness lower than the cement and hence neither the pozzolanic nor the filler effects could yield the strength of concrete higher than corresponding control even at 90 days. An important observation is that there is no significant difference in strength between control (0% fly ash) and 20% fly ash mixes but as replacement percentage increases further, a notable reduction in strength has been observed. However up to 30% fly ash replacements, all the concretes have yielded strengths exceeding or equal to 40 MPa at both the ages. Hence, adoption of fly ash as a partial replacement of cement has a tremendous potential in producing high strength high performance concrete. Neville has reported that using fly ash in a higher proportion exceeding 30% has adverse effect on strength [10] . But the results of the study indicate that with 40% fly ash replacement, it is possible to achieve quite high strength greater than 40 MPa at later ages i.e. 90 days. Higher amount of fly ash may be taken into consideration if such concrete is allowed to design for 90 days. In order to determine optimum fly ash percentage leading to strength similar to control, a detailed statistical analysis using linear regression technique has been performed using the data base of present investigation and accordingly strength prediction equations [2,3,6,7,9,15] dealing with most significant parameters (viz. w/cm and fly ash% as profusely reported in literature) have been formulated and are presented as follows:

For 28 days:
$\log_e (S_{28}) = 5.375 - 3.813 (w/cm) - 0.011 (f)$

For 90 days:
$\log_e (S_{90}) = 5.350 - 3.616 (w/cm) - 0.007 (f)$

where, ‘w/cm’ and ‘f’ refer to water-cementitious material ratio and fly ash percentage respectively while S_{28} and S_{90} are 28, 90 day compressive strength of concrete at 28 and 90 days respectively. Using these equations as a basis, optimum fly ash replacements have been calculated as 10% and 17% at 28 and 90 days respectively. According to numerous researchers, optimum fly ash content in concrete for strength maximization is not a constant but has mostly ranged from 10-30% [1, 8, 10, 16, 17]. For producing HSC, ACI has recommended a value of 15 to 25% as a fly ash replacement of Portland cement for Class F fly ash. The optimum values as obtained are less compared to some of the reporting which may be due to variation in fly ash quality.

4.3 Effect of water to cementitious material ratio on the compressive strength of concrete

A general observation of figures 1 and 2 indicates that as the water-cementitious material ratio increases, strength of control as well as the fly ash concrete decreases. This is valid at all the fly ash percentages and binder contents. Hence it may be inferred that century old Abrams w/c ratio law has been validated in the findings of present investigation with high strength concrete containing fly ash. At the two lower w/cm ratios viz. 0.27 and 0.306, fly ash concretes have resulted in quite high strength, equal to or greater than 50 and 60 MPa for fly as replacements up to 30% at 28 and 90 days respectively. On the other hand, for w/cm ratios of 0.342 and 0.378, fly ash concrete strength values are considerably less with respect to the lower w/cm ratios. Xu and Sarkar have reported that the effect of fly ash is more pronounced in richer mixes, concretes with higher paste content and a lower water binder ratio [5]. This is attributed to high concentration of alkalis and the increase in heat of hydration during early ages; both phenomena favour the fly ash reactions. It is also seen that as w/cm decreases from 0.342 to 0.306, a significant enhancement in strength has been observed for all replacement levels. Based on the observations it seems that high strength concrete incorporating fly ash may have a w/cm lower than 0.34. A study by Bentz and Aitcin [19] has indicated that the lower the w/c ratio, the closer the cement particles in the cement paste thereby forming the stronger links created by cement hydrates which contributes to significant strength enhancement. It is not necessary to have a large amount of cementitious gel in a low w/c paste to create strength. A high strength high performance concrete should have a w/cm, equal to or less than 0.35 as reported in previous publications [1, 16]. The results of the present investigation reinstate the observation of past researchers.

4.4 Effect of age on the compressive strength of concrete

Afer analyzing the figures on the effects of age on strength of concrete it may be inferred that all the fly ash mixes have gained considerable strengths from 7 to 28 days and strength development continues up to 90 days. Up to 28 days, strength development of fly ash concrete is almost similar to control, but beyond 28 days, rate of gain in strengths have increased with increasing fly ash percentages. It has been profusely reported that efficiency of fly ash to act as a cementitious material increases substantially at 28 days and strength development continues beyond 28 days and stabilizes at the age of almost 90 days. For the present study, the ratio of fly ash concrete strength between 7 and 28 days has been found to vary in the range of 0.57 to 0.73 with an average value of 0.61 whereas gain in strengths from 28 to 90 days varies from 9 to 27% with an average value of about 20%. Gopal Krishnan et al. (2001) working with a w/cm of 0.3 and fly ash replacements up to 30% have observed that 7 day strength of HSC containing fly ash varied from 58 – 65% of the strength of corresponding mixes at age of 28 days while gain in 90 days strength was from 5 – 14% over the strength at the age of 28 days. The ratio of the strength of concrete with OPC between 7 and 28 days is considered as 0.67.

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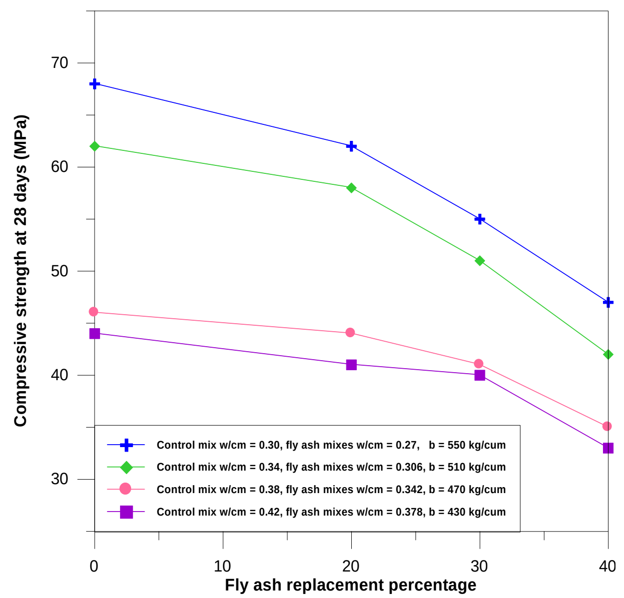

Figure 1. The relationship between 28 day compressive strength and fly ash replacement percentages

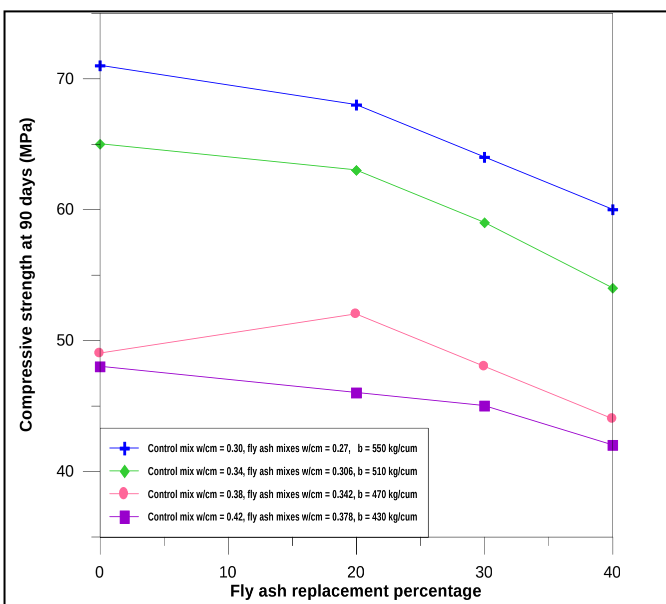

Figure 2. The relationship between 90 day compressive strength and fly ash replacement percentages

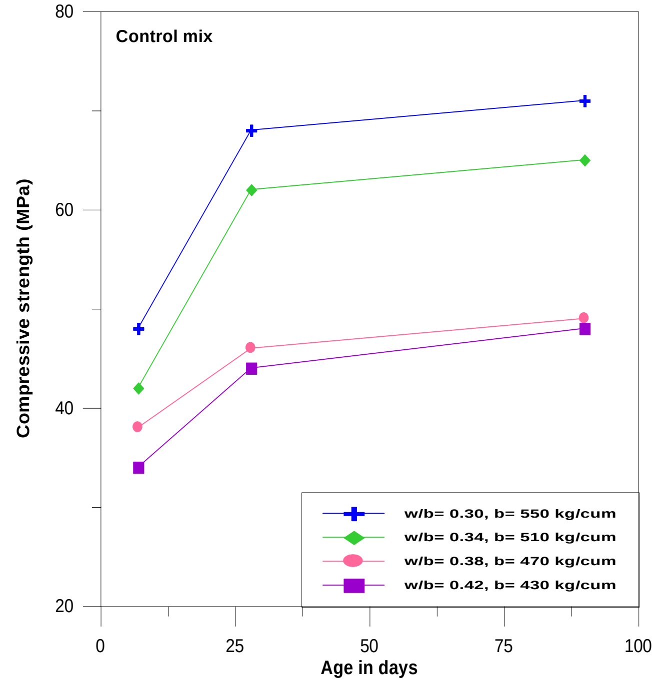

Figure 3. The relationship between compressive strength of control mixes and age

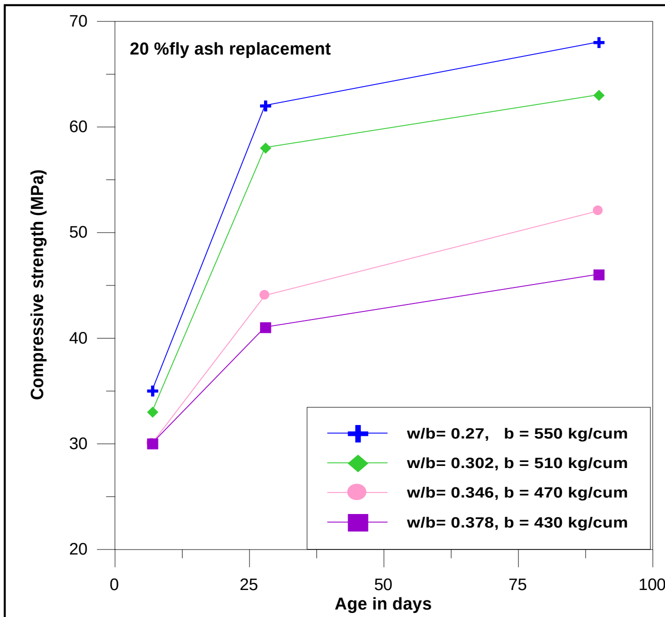

Figure 4. The relationship between compressive strength of 20% fly ash mixes and age

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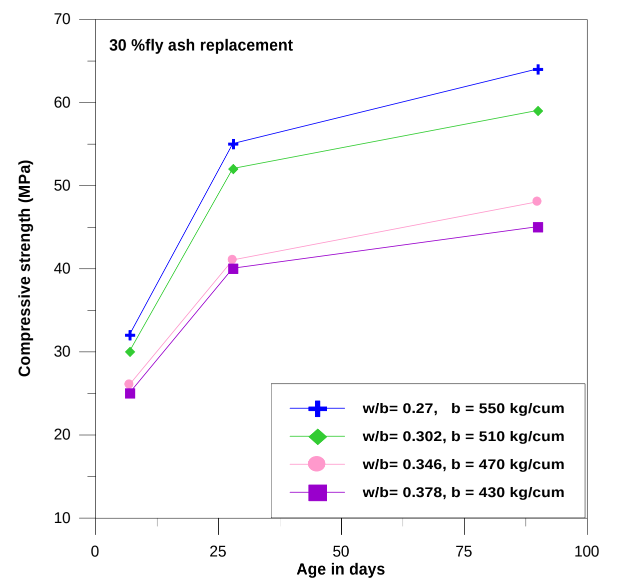

Figure 5. The relationship between compressive strength of 30% fly ash mixes and age

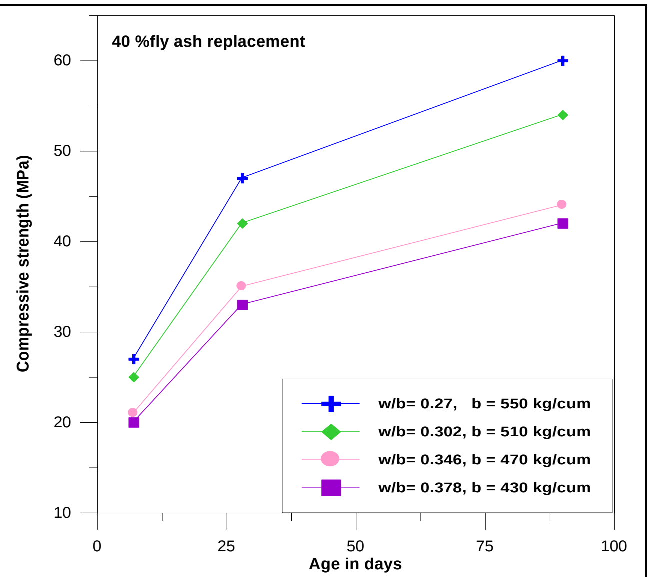

Figure 6. The relationship between compressive strength of 40% fly ash mixes and age

5. CONCLUSION

In the present investigation a total of 16 concrete mixes comprising of 4 controls and 12 fly ash mixes, have been investigated. The objective of the investigation was to explore the possibilities of an Indian fly ash in producing HSC and to evaluate the effect of some significant parameters affecting strength of fly ash concrete. A detailed experimentation has been undertaken over a wide range of w/cm ratios, binder contents and fly ash replacement levels at both early and later ages. Based on the results and the analyses presented herein the following conclusions can be drawn:

- **i.** At 28 day age level, compressive strength of concrete varied between about 33 to 68 MPa while that of 90 day strength has observed to vary in the range of 42 to 71 MPa.
- **ii.** Replacement of fly ash by equal weights of fly ash results in reduction in compressive strength at 28 and 90 days. Fly ash used in the investigation had a low reactive silica content and lower fineness compared to the cement and hence neither the filler effect nor the pozzolanic actions could yield higher strength with respect to control.
- **iii.** Up to 30% fly ash replacements, all the concrete mixes exhibited strengths exceeding or equal to 40 MPa at both the ages. Hence the proper use of fly ash has a tremendous potential in producing high strength high performance concrete. Higher proportion of fly ash like 40% can also be adopted if specified age for designing mixes is considered as 90 days.
- **iv.** Based on statistical analysis of the database of this work, optimum fly ash replacements have been calculated as 10% and 17% at 28 and 90 days respectively.
- **v.** Century old Abrams w/c ratio law which was originally formulated for concrete with cement as the only cementitious material is also valid for HSC containing fly ash. The results also suggest that high strength high performance concrete with fly ash as a partial replacement of cement can have a w/cm lower than 0.34.
- **vi.** Contribution of fly ash in improving strength of concrete increased with increase in replacement levels beyond 28 days. The average ratio of fly ash concrete strength between 7 and 28 days has been observed as 0.61 whereas gain in strengths from 28 to 90 days is about 20%.

6. ACKNOWLEDGEMENT

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REFERENCES

[1] ACI Committee 211 (1993), “Guide for Selecting Proportions for High Strength Concrete with Portland Cement and Fly ash”, ACI Materials Journal, Vol.90, No.3, pp. 272 – 283.

[2] Bharatkumar, B. H., Narayanan, R., Raghuprasad, B. K., Ramachandramurthy, D. S. (2001)., “Mix proportioning of high performance concrete”, Cement & Concrete Composites, Vol.23, pp. 71 – 80.

[3] Gopalan, M. K., Haque, M. N. (1986), “Strength development of fly ash concretes”, Engineering Materials and Structures, Vol.19, No.1, pp. 33-37.

[4] Mehta, P. K. (1985), “Influence of Fly Ash Characteristics on the Strength of Portland Fly Ash Mixtures”, Vol.15, pp.669 – 674.

[5] Xu, A., Sarkar, S.L. (1993), “Hydration and Properties of Fly ash Concrete”, in S.N.Ghosh edited Mineral Admixtures in Cement and

ISSN 2347-4289

Concrete, Progress in Cement and Concrete series, Akademia Books International, New Delhi, India, pp. 174 – 225.

[6] Slanicka, S. (1991), "The Influence of Fly Ash Fineness on the Strength of Concrete", Cement and Concrete Research, Vol.21, pp. 285 – 296.

[7] Popovics, S. (1982), "Strength Relationships for Fly Ash Concrete", ACI Journal, Vol.79, No.5, 1982, pp. 43 – 49.

[8] Oner, A., Akyuz, S., Yildiz., R. (2005), "An Experimental Study on Strength Development of Concrete Containing Fly Ash and Optimum usage of Fly Ash in Concrete", Cement and Concrete Research, Vol.35, pp. 1165 – 1171.

[9] Oluokun, F. A. (1994), "Fly Ash Concrete Mix Design and the Water - Cement Ratio Law", ACI Materials Journal, Vol.91, No.4, pp. 362 – 371.

[10] Neville, A. M. (1996), "Properties of Concrete", Fourth Edition ELBS with Addison Wesley Longman Limited, England.

[11] IS: 8112-1989, Indian Standard, "Specification for 43 Grade Ordinary Portland Cement". Bureau of Indian Standards.

[12] IS: 3812(Part 1 & 2)-2003, Indian Standard, "Pulverized Fuel Ash - Specification". Bureau of Indian Standards.

[13] Pan, S., Bhanja, S., (2012) "Strength Prediction Models for Fly ash concrete" UKIERI Concrete Congress Innovations in Concrete Construction, Jalandhar, India, 5-8 March.

[14] Bhanja, S., Pan, S., (2013) " Modified Water cement ratio law for fly ash concrete" The Indian Concrete Journal, Vol.87, No.10, pp. 21 –28, October, 2013.

[15] Pan, Samaresh (2013), "Effect of Fly Ash as a Cement replacement material on the characteristics of concrete" PhD dissertation, Jadavpur University, Kolkata, India.

[16] Gopalakrishnan, S., Rajamane, N. P., Neelamegam, M., Peter, J. A., Dattatreya, J. K. (2001), "Effect of Partial Replacement of Cement with Fly ash on the Strength and Durability of HPC", The Indian Concrete Journal, pp.335 – 340.

[17] Haque, M. N., Kayali, O. (1998), "Properties of High-Strength Concrete Using a Fine Fly Ash", Cement and Concrete Research, Vol.28, No.10, pp. 1445 – 1452.

[18] Bhanja, S., Sengupta, B. (2003), "Modified water-cement ratio law for silica fume concretes", Cement and Concrete Research, Vol.33, pp. 447 – 450.

[19] Aitcin, P. C. (1984), "High performance Concrete", E & FN SPON, London, England.