Effect of relative proportion of pozzolana on compressive strength of concrete under different curing conditions

Shweta Goyal shweta@tiet.ac.in
Lecturer/Civil Engineering Department
Thapar University
Patiala, 147004, India

Maneek Kumar maneek@thapar.edu
Professor/Civil Engineering Department
Thapar University
Patiala, 147004, India

B. Bhattacharjee bishwa@civil.iitd.ac.in
Professor/Civil Engineering Department
IIT Delhi
New Delhi, India

Abstract

In this experimental and analytic research, the effect of curing regime on various combinations of silica fume and fly ash was investigated in terms of development of compressive strength. Over 24 mixes were prepared with the water-to-binder ratios of 0.45, 0.35 and 0.25 and with differing percentage of additives used as a combination of 2 or 3 binders. The specimens were subjected to five different curing regimes ranging from continuously water cured to continuously air cured. Results show that it is economical to use a combination of silica fume and fly ash rather than using only silica fume for attaining the same strength level. Poor curing condition adversely affect the strength characteristics of pozzolanic concrete than that of OPC concrete. For silica fume concrete, it is necessary to apply water curing for the initial 7 days to explore pozzolainc activity but it is imperative to cure the fly ash concrete for an extended period to utilize its full potential.

Keywords: strength, curing, ternary, silica fume, fly ash

1. INTRODUCTION

Mineral admixture concrete is one of the most significant new material available worldwide for new construction and for rehabilitation purposes. Studies have shown [1 –4] that mineral admixtures such as blast furnace slag, fly ash and silica fume enhance the strength and durability of concrete. Research concerning the use of mineral admixtures to augument the properties of concrete has been going on for many years. Economics (lower cement requirement) and environmental considerations also have a role in the growth of mineral admixture usage. The lower cement requirement leads to a reduction in the amount of carbon dioxide generated by the production of cement and hence its emission to atmosphere [5, 6].

The addition of wide range of blending material also introduces significant diversity into the cementing system. For instance, addition of silica fume increases early strength of concrete by formation of secondary C-S-H at early stages due to fast pozzolanic reaction [7 – 9]. However, it decreases the flowability of fresh concrete due to its very fine particles and hence the properties of silica fume can be enhanced by the presence of superplasticizers in the mix [6]. Unlike silica fume, fly ash mixes require longer period of time to develop strength [10]. At 28 days, the degree of fly ash reaction rate is slightly more than 10 percent [11 – 14]. However, fly ash leads to workability enhancement due to its spherical particles that easily role over one another reducing inter particle friction (called ball bearing effect) [15]. In India, silica fume comes under the category of costly materials and fly ash is abundantly available worldwide and its production is ever increasing. Therefore, a combination of silica fume and fly ash can be a better option in terms of modifying the properties (fresh and hardened) of resultant concrete and in terms of economy.

Over the past several decades, numerous failures of concrete structures during construction due to accelerated construction schedules have emphasized the early age strength gain of concrete [16] and importance of minimum days of curing for concrete [17]. In the standards, the minimum curing periods under certain weather conditions are specified. For most of the structures, initial moist curing for 7 days is essential [19]. The reported longer curing period required for blended cement concretes, as opposed to plain cement concrete, is still a question often debated among concrete technologist. Since pozzolanic reaction is highly dependent on good curing practice, there is often concern as to the effect of curing for pozzolanic cement concrete. Many investigators [19 – 21] believe that a curing period of about 28 to 90 days is required for pozzolanic cement concrete specimens to attain properties superior to that of plain cement concrete. However, not much research has been carried out on strength development characteristics of ternary mixes containing a combination of OPC – silica fume and fly ash.

This research is intended to expand the knowledge concerning the relative performance of a range of mixes made with OPC, silica fume and fly ash either as binary or ternary combinations. The performance evaluation has been carried out in terms of mechanical properties which include compressive strength, tensile strength and permeability under five different curing conditions. Based on the test results, the effect of relative percentage of ingredients, water – binder ratio and curing condition has been discussed. Also, the effect of wet – dry cycling condition on the deterioration mechanism of short-term cured concrete is studied.

2. EXPERIMENTAL PROGRAM

2.1. Materials:

2.1.1. Cementatious material: ASTM Type I Portland cement is used in this study. Its chemical composition is given in Table 1. The chemical and physical characteristics of two mineral admixtures silica fume and fly ash are also given in Table 1.

2.1.2. Aggregates: Crushed granite with a maximum nominal size of 10 mm was used as coarse aggregate and natural riverbed sand confirming to Zone II with a fineness modulus of 2.52 was used as fine aggregate. The properties of aggregates are listed in Table 2.

2.1.3. Super-plasticizer: Polycarboxylic group based superplasticizer, Structro 100 (a product of Fosroc chemicals), is used throughout the investigation. This group maintains the electrostatic charge on the cement particles and prevents flocculation by adsorption on the surface of cement particles [22]. It is a light yellow coloured liquid complying with requirements of IS 9103 – 79, BS 5075 Part III and ASTM – C494 Type F. The specific gravity of superplasticiser is 1.2 and solid content is 40 percent by mass.

1 Table 1: Physical, chemical and strength characteristics of cement

Characteristic	OPC	SF	FA
Physical Tests			
Normal Consistency (%)	32		
Vicat (hour: minute)			
Initial	2:10		
Final	4:08		
Specific Gravity	3.12		2.42
Le-Chatelier (mm)	1.5		
Fineness (% retained on 90 micron sieve)	3.2		
Particle shape	Angular	Spherical	Spherical
Mean particle diameter (µm)		19.6	0.1
Chemical			
CaO(%)	61.7	0.5	1.7
SiO_2 (%)	22.4	90.7	56.8
Al_2O_3(%)	5.93	0.68	25.8
Fe_2O_3(%)	4.91	2.2	6.43
SO_3(%)	2.28		1.4
MgO(%)	1.5	1.47	0.6
K_2O(%)	0.65	0.9	0.79
Na_2O(%)	0.122	0.86	0.36
Loss on ignition(%)	1.27	2.5	2.15
Insoluble Residue(%)	4.52		84.9
Blaine fineness (m^2/kg)	287.8	19.7	
Density (kg/m^3)	3150	650	
Accelerated pozzolanic activity index (7 days) %		98	
Strength			
f_c (3 days) (MPa)	26.5		
f_c (7 days) (MPa)	36.2		
f_c (28 days) (MPa)	47.3		

Table 2: Properties of aggregates

Property	2 FA	3 CA
Unit mass (kg/m^3)	1.692	1.68
Specific gravity	2.54	2.64
Percentage absorption (%)	1.95	1.12
Sieve Analysis	Cumulative percentage retained (%)	
20mm	0	0
10 mm	0	2.5
4.75 mm	5.05	92.8
2.36 mm	9.55	98.6
1.18 mm	17.6	100
600µ	44.6	100
300µ	80.15	100

2.2. Specimen Details and Preparations:

Three series of concretes were produced in this study corresponding to three water-to-binder ratios: 0.45, 0.35 and 0.25 to ensure wide variation of strength. For each series, eight separate batches were prepared: one control, 3 mixes containing different percentage of silica fume and fly ash and 4 made of combinations of silica fume and fly ash. The slump of the fresh concrete was kept in the range of 200±20 mm. A pre-study was carried out to determine the optimum super-plasticizer dosage for achieving the desired workability based on the slump cone test ASTM C 143 – 90 (a) [23]. The mix details of specimens are listed in Table 3 and Table 4. Mixing water was adjusted to correct for aggregate absorption and for the additional water brought into mix from superplasticizers.

Table 3: Mix proportions for control mixes

Water binder ratio	Mix proportions (kg/m^3)				Mix Ratio
	Cement	F.A.	C.A.	Water	
0.25	520	521.1	1340.4	130	1:1.042:2.681
0.35	457.1	523.9	1283	160	1:1.146:2.807
0.45	422.2	556.8	1183.3	190	1:1.319:2.802

Table 4: Details of mixes

Mix type	Notation	W/B	OPC (%)	Mineral admixture (% replacement of OPC)		Superplasticizer dosage (wt. Percent of binder)
				SF	FA	
Control mixes	M1	0.25	100	-	-	4
	M2	0.35	100	-	-	1.25
	M3	0.45	100	-	-	0.2
Binary mixes	M1BS1	0.25	95	5	-	3.75
	M1BS2	0.25	90	10	-	4.25
	M1BF1	0.25	70	-	30	2
	M2BS1	0.35	95	5	-	1.5
	M2BS2	0.35	90	10	-	2
	M2BF1	0.35	70	-	30	0.5
	M3BS1	0.45	95	5	-	0.3
	M3BS2	0.45	90	10	-	0.7
	M3BF1	0.45	70	-	30	0.1
Ternary mixes	M1TC1	0.25	80	5	15	3.25
	M1TC2	0.25	75	5	20	2.75
	M1TC3	0.25	75	10	15	3.5
	M1TC4	0.25	70	10	20	3.25
	M2TC1	0.35	80	5	15	1
	M2TC2	0.35	75	5	20	0.75
	M2TC3	0.35	75	10	15	1.5
	M2TC4	0.35	70	10	20	1.25
	M3TC1	0.45	80	5	15	0.1
	M3TC2	0.45	75	5	20	0.1
	M3TC3	0.45	75	10	15	0.4
	M3TC4	0.45	70	10	20	0.3

2.3. Testing procedure:

Concrete batches were mixed in a pan mixer for 3 minutes. $150 \times 150 \times 150 - mm^3$ cubes were cast for the compressive strength tests. The specimens were cast in accordance with ASTM C 192 – 88 [24]. Plastic sheets were used to cover the specimens to prevent water from evaporating. After 24 hours, the specimens were striped from their respective molds and the curing regime as given in Table 5 was applied. The strength tests were carried out at 1, 3, 7, 14, 28, 56, 90 days taking the average of six specimens for each test. In the case of mixes prepared at water binder ratio of 0.25, the specimens were stripped off after 36 hours and therefore, the compressive strength studies were started at the end of 2 days instead of 1 day. The test procedure followed during the test was in conformity with BS 1881:Part 116:1983 [25]

Table 5: Summary of curing regimes adopted

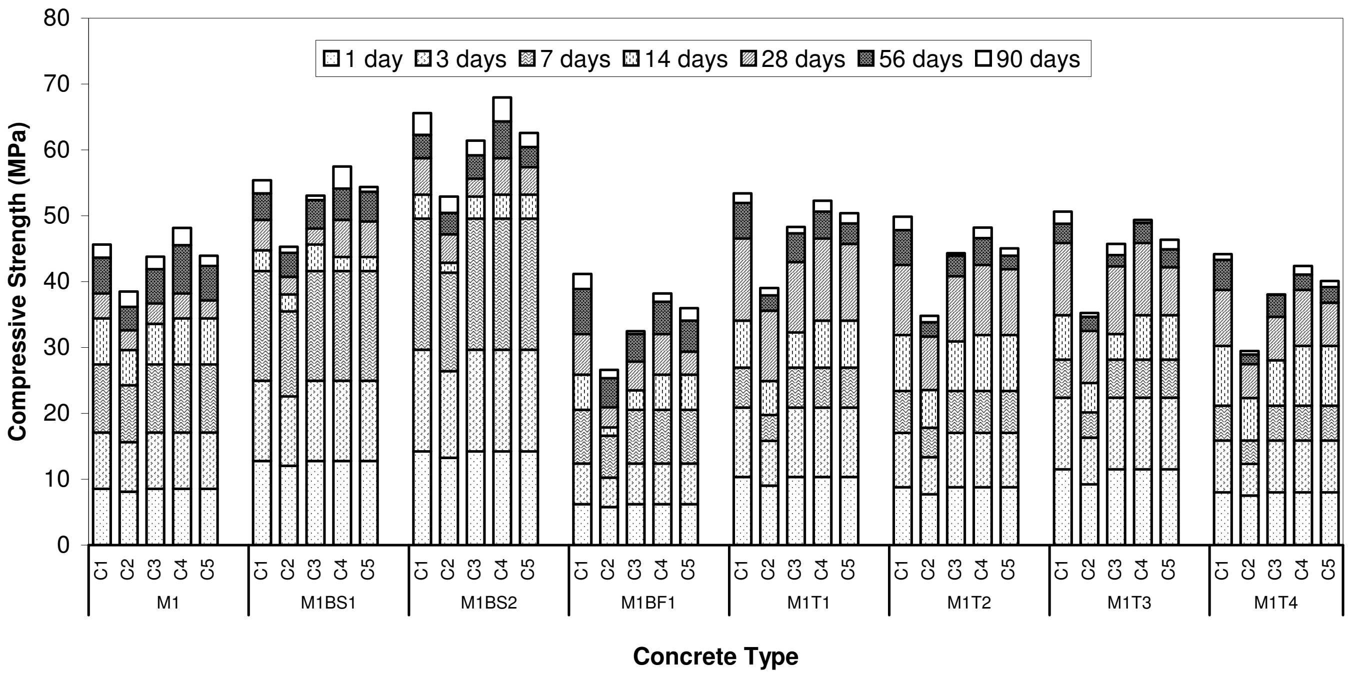
Curing Regime 4	Description
1.	Continuously water curing at temperature of 25 ± 2°C
2.	Continuously air curing in the lab environment at around 25 ± 5°C and 50± 10% RH
3.	Initial 7 days of water curing followed by air drying (as in No. 2)
4.	Initial 28 days of water curing followed by air drying (as in No. 2)
5.	Initial 14 days of water curing followed by wetting and drying cycles of 7 days duration

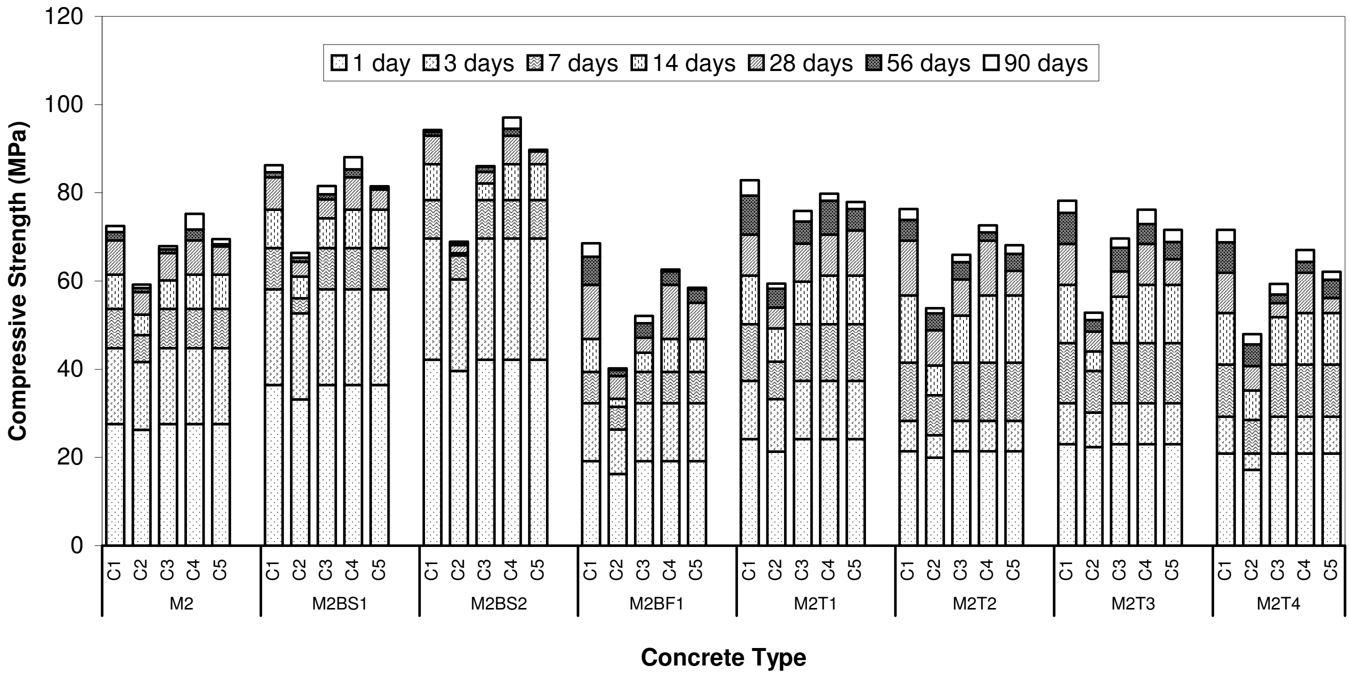
3. RESULTS AND DISCUSSIONS

3.1 Compressive strength results

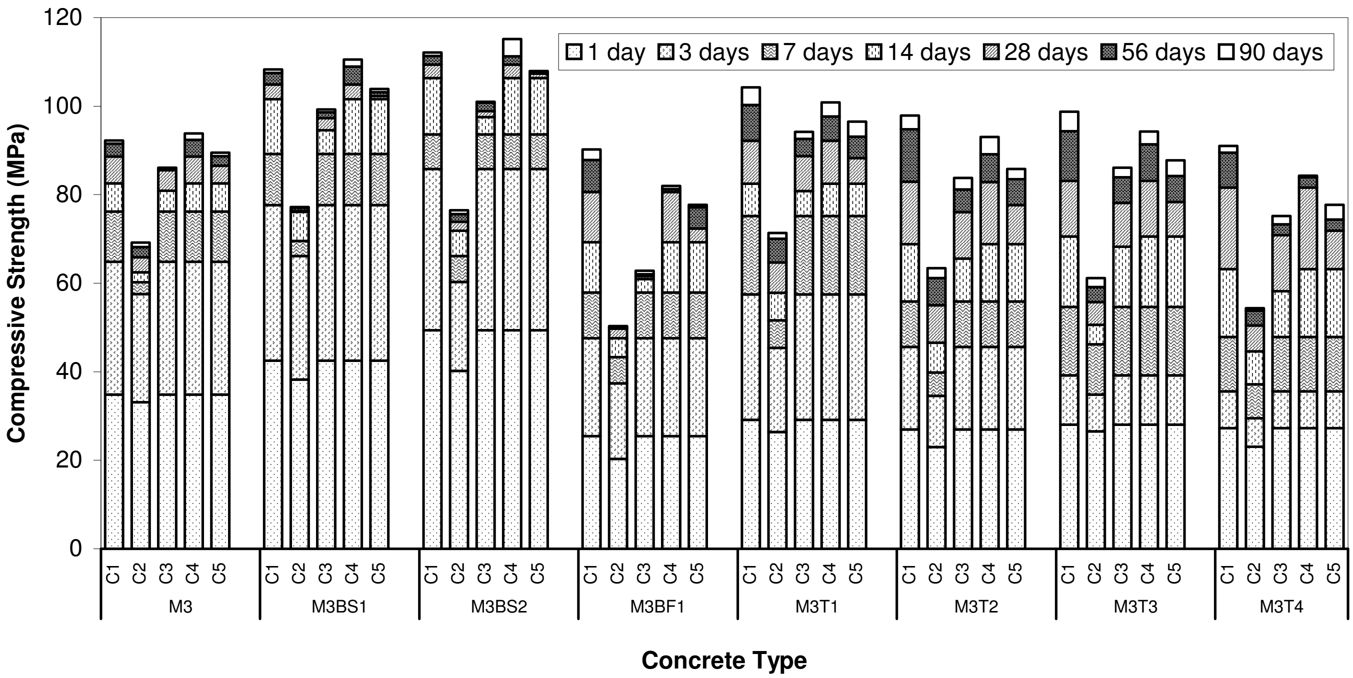
The compressive strength development is illustrated in Figs. 1 *(a to c)* for water binder ratios of 0.45, 0.35 and 0.25 respectively.

(a) water binder ratio: 0.45





(b) water binder ratio: 0.35

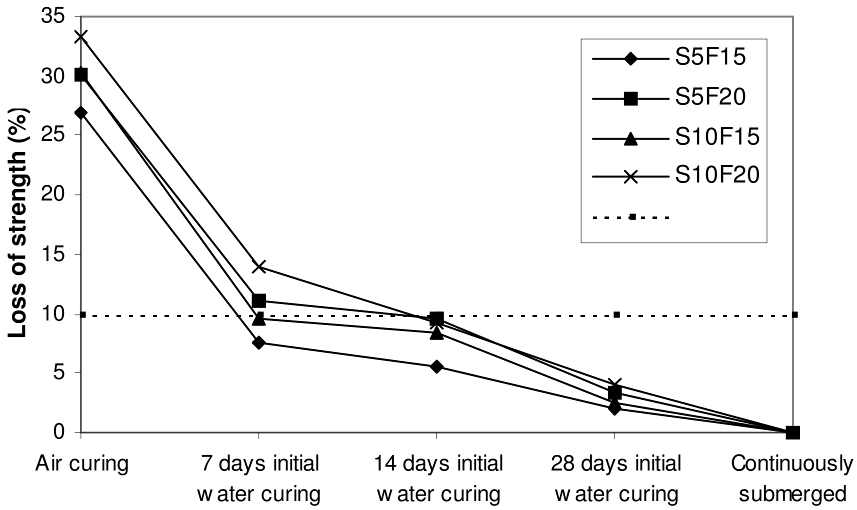


(c) water binder ratio: 0.25

Fig. 1 Variation of compressive strength development of plain and blended concrete

3.1.1. Effect of supplementary cementatious materials

The addition of silica fume produced the increase in strength while addition of fly ash produced



(ii) Ternary mix

decrease in strength for all water-to-binder ratios. The better performance of silica fume concrete could be attributed to the improvement in the bond between the hydrated cement matrix and aggregate. This is due to the combined effect of secondary pozzolanic reaction and extremely fine silica fume particles [27, 28]. Among silica fume concrete mixes also, the compressive strength increases as the percentage replacement is increased from 5% to 10%.
The combination of silica fume and fly ash leads to increase in compressive strength as compared to control mix at all water binder ratios. The combination of 5% silica fume, 15% fly ash and 80% cement performed best among the four combinations studied and produced an increase in strength of about 17%, 12.5% and 13.3% respectively at water binder ratios of 0.45, 0.35 and 0.25 over the control mix. This combination produced strength almost similar to the strength of mix having 5% silica fume and 95% cement.

3.1.2. Effect of curing regime

In Fig. 1, it is common that air cured specimens gained the lowest strength for all mixes and at all ages. In general, compressive strength of concrete increased with increase in initial water curing period. This general trend has some exceptions in the case of OPC and silica fume concrete mixes. These mixes exhibit higher strengths at 56 and 90 days when initially water cured for 28 days (C4 curing condition) as compared to continuously submerged specimens (C1 curing condition). The higher strength of partial dried specimens can be attributed to the increase in secondary forces between the surfaces of cement gel [26, 31] and also to the reduction in disjoining pressure due to drying [17].

The average difference between compressive strength at two extreme curing conditions, continuously air cured and continuously water cured, is smaller for OPC concretes than those for pozzolanic concretes showing that mineral admixture concrete is more sensitive to inadequate curing than OPC concrete, as indicated previously [17, 32]. This can be attributed to the lack of development of hydration and pozzolanic reactions to produce a dense microstructure and the extensive shrinkage cracking which may have developed due to air curing as is indicated by other researchers [33, 34].

In order to find the days of initial water curing that is both necessary and sufficient for all mixes, percentage loss of strength under the given curing condition with reference to the submerged condition at 90 days is plotted against the initial curing period (Figs. 2 to 4). From the Figs. 2 to 4, it is clear that continuous air curing leads to very high loss of strength and should never be considered as a curing practice. Also, if 7 days of initial curing practice is adopted, then binary mixes with silica fume and ternary mixes (T1 and T3) are able to reach 90% of strength of continuously water cured specimens. It can be concluded that 7 days of initial water curing is sufficient to explore the pozzolanic activity for these mixes.

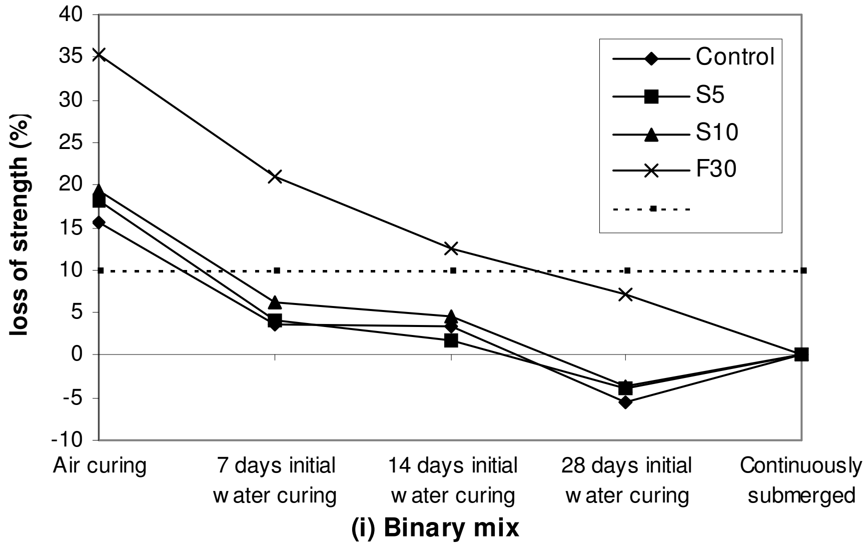
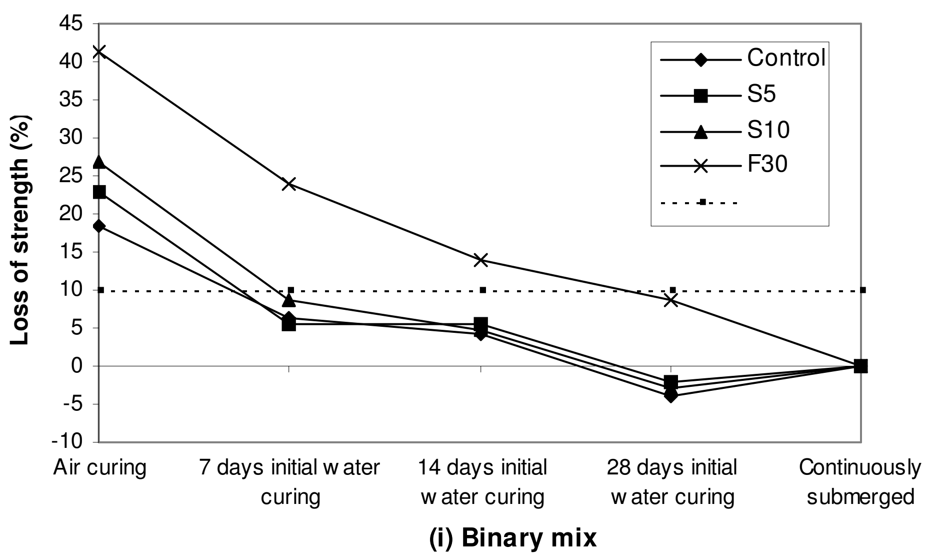
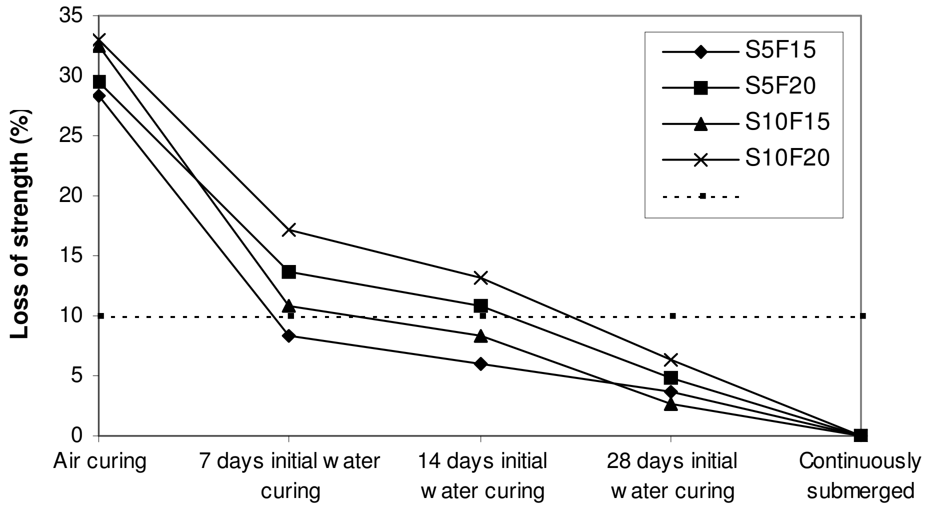


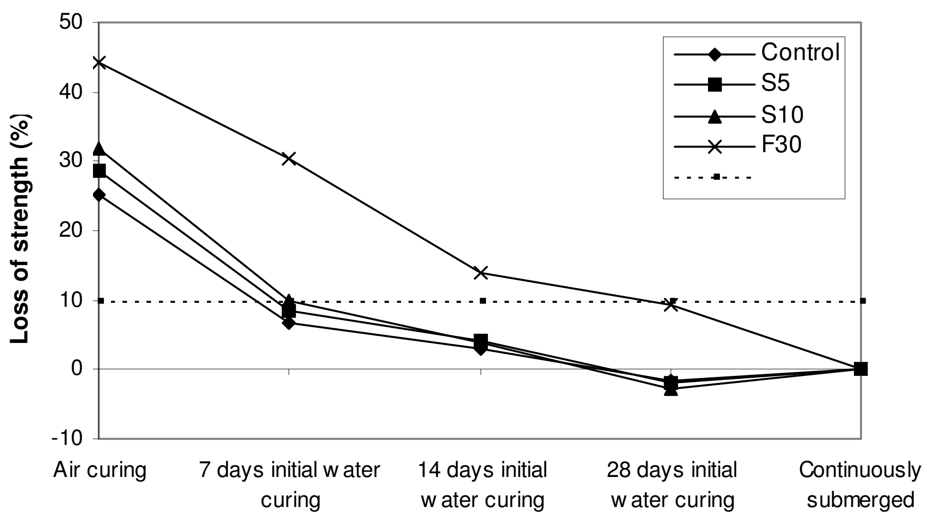
Fig. 2 Percentage loss of mixes compared to continuously submerged condition at water binder ratio of 0.35.



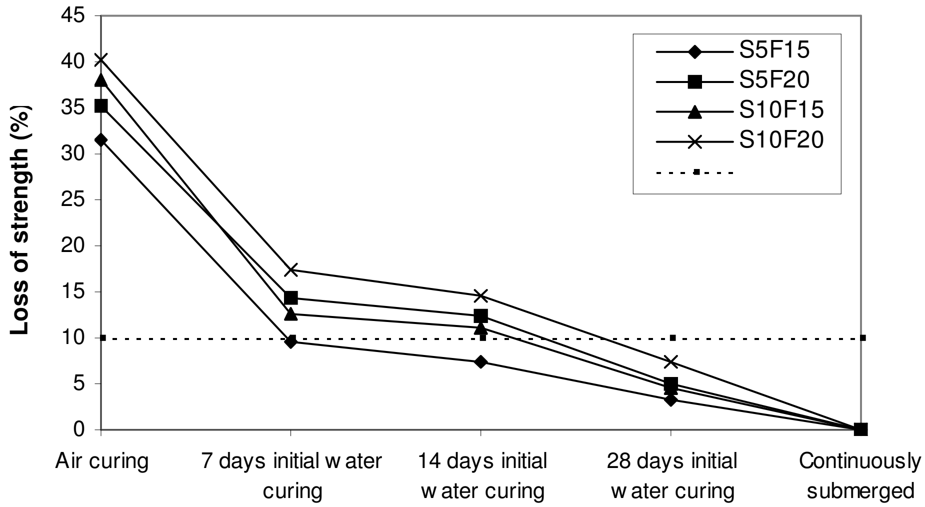


(ii) Ternary mix

Fig. 3 Percentage loss of mixes compared to continuously submerged condition at water binder ratio of 0.35.



(i) binary mix



(ii) Ternary mix

Fig. 4 Percentage loss of mixes compared to continuously submerged condition at water binder ratio of 0.25.

The strength development of mixes was further analyzed by using the equation:

$$f_c = aLn(t) + b$$

where f_c is the compressive strength of concrete at t days, *a* and *b* are constants. The constants *a* and *b* are obtained from least square method and are given in Table 6. The correlation coefficients are quite high (mostly > 0.95) for almost all the mixes.
In this equation, constant *a* represents the strength gaining rate of concrete. From the table, it seems that the strength-gaining rate is less sensitive to initial water curing at higher water binder ratios and becomes more and more sensitive as the water binder ratio is decreased. Also, the strength – gaining rate is sensitive for mixes containing fly ash confirming that fly ash concrete is more affected by the curing practice adopted.

Mix Type	Control		BS1		BS2		BF1	
Regression constants	a	b	a	b	a	b	a	b
Curing Regime	Water-to-binder ratio = 0.45							
R1	8.51	9.38	9.5	16.5	11.28	19.23	8.13	4.93
R2	6.85	9.23	7.35	15.65	8.55	17.77	4.69	5.86
R3	8.02	9.76	9.03	17.11	10.28	20.32	6.1	6.84
R4	9.02	8.73	9.83	15.92	11.79	18.69	7.56	5.65
R5	8.11	9.8	9.37	16.53	10.64	20.04	6.85	6.32

	Water-to-binder ratio = 0.45							
R1	9.99	32.13	10.84	43.19	10.99	52.12	11.29	18.97
R2	7.05	31.32	6.69	40.23	5.5	48.75	5.22	19.18
R3	8.86	33.16	9.46	44.27	8.7	53.78	7.05	22.93
R4	10.4	31.58	11.13	42.81	11.41	51.55	10.2	20.36
R5	9.27	32.93	9.75	44.36	9.82	53.31	9.06	21.47
	Water-to-binder ratio = 0.45							
R1	12.59	43.03	14.42	52.65	13.76	60.35	15.84	24.28
R2	7.05	41.12	7.61	48.85	7.78	46.06	6.44	25.87
R3	10.85	45.21	11.58	55.4	9.94	63.66	7.64	34.15
R4	12.92	42.51	14.92	51.87	13.91	59.59	13.83	27.37
R5	11.72	44.19	13.1	54.45	12.28	62	12.25	29.14

Table 6: Strength development constants of control and binary mixes

Mix Type	TC1		TC2		TC3		TC4	
Regression constants	a	b	a	b	a	b	a	b
Curing Regime	Water-to-binder ratio = 0.45							
R1	10.14	9.43	9.78	7.1	9.08	11.83	8.7	6.96
R2	7.2	7.94	6.55	6.83	6.15	9.25	5.34	7.17
R3	8.84	10.56	8.59	8.35	7.78	9.25	7.17	8.29
R4	9.87	9.76	9.45	7.52	8.93	12.04	8.26	7.51
R5	9.4	10.3	8.75	8.34	7.96	12.95	7.68	8.09
	Water-to-binder ratio = 0.45							
R1	13.54	24	13.64	18.26	13.23	21.47	12.13	19.06
R2	8.63	23.69	8.26	18.6	6.96	23.79	7.37	15.23
R3	11.95	25.66	10.87	20.45	11.01	23.41	9.03	22.27

R4	13.04	24.66	12.89	19.21	12.72	22.09	11.11	20.32
R5	12.66	25.21	11.48	20.44	11.56	23.28	9.78	21.56
	Water-to-binder ratio = 0.45							
R1	17.4	31.92	18.02	20.57	18.8	17.95	17.9	15.64
R2	10.47	28.05	10.09	19.92	8.68	25.13	8.37	20.04
R3	14.8	35.43	13.94	25.82	15.4	22.45	13.01	21.53
R4	16.59	33.18	16.65	22.64	17.78	19.53	16.24	18.2
R5	15.2	35	14.61	25.37	15.72	22.29	13.59	21.39

Table 7: Strength development constants of ternary mixes

4. CONCLUSION

The present research focused on studying the effect of silica fume and fly ash either in binary mix or in ternary mix on strength of concrete and to determine how curing conditions affects concrete strength. Based on the results obtained the following conclusions can be drawn:

1. Specifying concrete on the basis of 28 days compressive strength under estimates the general beneficial effects of mineral admixture concrete. Water binder ratio, cement type, age and curing conditions have significant effect on strength characteristics of concrete.
2. It is economic to use a combination of silica fume and fly ash rather than using only silica fume as mineral admixture for attaining the same strength level. Among the ternary mixes, Mix T1, with a combination of 5% silica fume and 15% fly ash, showed the highest increase in strength for the entire range of water binder ratios. Using T1 mix leads to 10 to 15% cost saving as compared to mix with 5% silica fume and no fly ash.
3. Continuous air curing is worst curing regime for all mixes. Although, the curing conditions affect the strength of both OPC concrete and mineral admixture concrete, however, pozzolanic concretes are more adversely affected by poor curing practices than OPC concrete. For totally submerged curing condition, strength gaining rates of OPC concrete is lower than mineral admixture concrete. However, the trend becomes opposite for air curing condition.
4. For silica fume concrete and for a ternary combination that has lesser amount of fly ash in it, 7 days of initial water curing is both necessary and sufficient to explore the pozzolanic activity. However, for mixes having larger percentage of fly ash, a long initial moist curing period is necessary to fully benefit from the addition of these supplementary cementatious materials. Replacing cement by percentage greater than 20% tends to lower the efficiency of mineral admixtures. At this replacement level, the pozzolanic reaction start becoming lime controlled instead of being pozzolana controlled. If the percentage replacement of cement reaches 30%, the strength of resultant mix is even lesser than the corresponding control mix.

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