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Early-Age Strength Development of Concrete Incorporating Fly Ash and Condensed Silica Fume

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Synopsis: Early-age strength development of concrete in which part of the portland cement has been replaced by low-calcium fly ash tends to be slow, because fly ash acts as a relatively inert component during this period of hydration, though at later ages it contributes significantly to strength development. It was considered that the problem of low early-age strength of portland cement-fly ash concrete could be overcome by the incorporation of small amounts of condensed silica fume, a very fine and more rapidly reactive pozzolan.

This report presents the results of an investigation on the early-age strength development of concrete incorporating 30% low-calcium fly ash, and to which small amounts of condensed silica fume have been added. The amounts of the fume ranged from 0 to 20% by combined weight of the portland cement plus fly ash. A total of thirty 0.06-m^3 concrete mixtures with water-(cement + fly ash) ratios ranging from 0.40 to 0.80 were made; 240 cylinders were tested in compression and 180 prisms were tested in flexure. A supplementary series of six concrete mixtures was made to determine the effect of silica fume and fly ash on the long-term strength development of concrete.

Test data showed that the incorporation of condensed silica fume increased the compressive strength of concrete at all ages as compared with the compressive strength of the control concrete (70% portland cement + 30% fly ash). At 7 days, the loss of compressive strength due to the partial replacement of cement by fly ash was completely overcome by the addition of 10% condensed silica fume for concretes with water-(cement + fly ash) ratios ranging from 0.40 to 0.60; 15 to 20% was required for concretes with higher water-(cement + fly ash) ratios. At 28 days, regardless of the water-(cement + fly ash) ratio, the effect was generally achieved with less than 5% silica fume addition. The later-age strength development of portland cement-fly ash concrete did not appear to be impaired by the use of condensed silica fume indicating availability of sufficient lime for the fly ash pozzolanic activity.

Keywords: age-strength relation; compressive strength; concretes; fly ash; plasticizers; pozzolans; silica.

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INTRODUCTION

Over the past five years, CANMET has undertaken a number of research projects involving the use of slags and pozzolans in concrete (1-6). One of the pozzolans being considered is condensed silica fume, and several research reports dealing with the use of this material have been published (7-9). These were concerned primarily with the use of silica fume as a partial replacement for or addition to portland cement.

It is known that early-age strength of concrete incorporating materials such as slag and fly ash is generally lower than the strength of control concrete, even though the later-age strength development of such concrete is equal to or higher than the control concrete. It was considered that the use of condensed silica fume in fly ash or slag concrete might overcome the problem of low early-age strength. Metha and Gjørv have reported limited data using this approach (10).

This report gives results of laboratory investigations to determine the early-age strength development of concrete containing 30% of fly ash as a partial replacement for cement and incorporating various percentages of condensed silica fume.

SCOPE OF INVESTIGATION

A total of thirty-six 0.06-m^3 concrete mixtures were made to evaluate the performance of condensed silica fume in portland cement-fly ash concrete. The investigation was divided into two series.

(1) Series A - To determine the early-age strength development of portland cement-fly ash concrete incorporating 0 to 20% condensed silica fume by weight of cement plus fly ash. The W/(C+F)* of the 30 mixtures ranged from 0.40 to 0.80.

*Water-(Cement + Fly Ash) ratio

(2) Series B - To determine both the early- and later-age strength development of portland cement-fly ash concrete incorporating 0 to 20% silica fume by weight of cement plus fly ash. The W/C+F) of the six mixtures was kept constant at 0.60.

MATERIALS

The concrete mixtures were made using the following materials:

Cement

Normal portland cement, CSA Type 10 (ASTM Type 1), was used. Its physical properties and chemical analysis are given in Table 1.

Fly Ash and Condensed Silica Fume

Fly ash, CSA Type F (ASTM Class F), and condensed silica fume, both from Canadian sources, were used. Their physical and chemical properties are also given in Table 1.

Aggregates

The coarse aggregate was crushed limestone passing the 19.0 mm sieve and the fine aggregate was local natural sand. To keep the grading uniform for each mixture, both the fine and coarse aggregates were separated into different size fractions which were then recombined to a specific grading.

The relative density and absorption of the coarse aggregate were 2.70 and 0.70% respectively, the corresponding values for the fine aggregate were 2.68 and 1.1%.

Superplasticizer

A sulphonated naphthalene formaldehyde condensate was used. It is available as a dark brown 42% solids aqueous solution having a density of 1200 kg/m^3. The chloride content is negligible.

Air-entraining Agent

The air-entraining agent (A.E.A.) was of the sulphonated hydrocarbon type.

CONCRETE MIXTURES

Mixture proportions are summarized in Table 2. The mixture referred to as the reference concrete did not contain any fly ash or condensed silica fume. The mixture referred to as the control concrete incorporated 30% fly ash by mass as partial replacement for cement. The test mixtures were identical to the control mixture except that they contained additions of 5, 10, 15 and 20% of condensed silica fume by mass of cement plus fly ash.

The room-dry coarse and fine aggregates were soaked for 24 h before mixing and the amount of mixing water was subsequently adjusted according to the water absorbed. Concrete was mixed in a laboratory counter-current mixer. The mixing sequence consisted of the addition to the mixer of: the coarse aggregate, part of the mixing water, cement, fly ash, fine aggregate, air-entraining admixture and the remaining mixing water. The condensed silica fume and superplasticizer, when used, were added after a 3-min mixing of all of the above ingredients. The total mixing time varied from 9 min for the reference mixtures to 12 min for those with 20% condensed silica fume.

The control and test mixtures were proportioned to have a slump of 80 ± 15 mm and an air content of 6 ± 0.5%, except for mixes with a W/(C+F) of 0.40 for which the air content was set at 5 ± 0.5%. With minor exceptions the above requirements generally were met for the mixtures of Series A. However, there was some difficulty experienced in maintaining the rigid air content requirements for the test mixtures of Series B; consequently, air contents of 6 ± 1.0% were tolerated.

The properties of the fresh concretes are given in Table 3. For any given W/C+F, the water content was kept constant. Any loss in slump due to the incorporation of the condensed silica fume was compensated for by the use of a superplasticizer.

CASTING AND CURING OF TEST SPECIMENS

Mixture Series A

Eight 152 x 305-mm cylinders and six 76 x 102 x 406-mm prisms were cast from each mixture. The cylinders were cast in two layers, each layer being compacted by an internal vibrator. The prisms were cast in two layers, each layer being compacted using a vibrating table. The moulded specimens were covered with a water-saturated burlap and left in the casting room for 24 h after which they were demoulded and transfered to a moist-curing room maintained at 23 ± 1.7°C and 100% relative humidity until required for testing.

Mixture Series B

Eighteen 102 x 203-mm cylinders were cast from each mixture. The cylinders were cast in two layers each layer being vibrated using a vibrating table. The test specimens were cured in the same manner as those in Series A.

TESTING OF SPECIMENS

The specimens were tested in compression and flexure at various ages in accordance with the testing schedule shown in Table 4. As far as possible, all tests were made according to

ASTM Standards. Before testing in compression, specimens were capped with a sulphur-based mixture.

TEST RESULTS

A summary of the test results for mixture series A and B are shown in Tables 5 and 6, and the data are illustrated in Figures 1 to 10.

DISCUSSION OF TEST RESULTS

Handling of Condensed Silica Fume

Because of its extreme fineness, condensed silica fume may present handling problems in the field. However, in this laboratory investigation, no such problems were encountered, though all laboratory staff taking part in the mixing program wore disposable masks.

Properties of Fresh Concrete

The replacement of 30% of the cement by fly ash was generally found to result in slight increase in slump. For the mixtures incorporating condensed silica fume, the loss of slump was compensated for by the use of a superplasticizer. As expected, the quantity of superplasticizer needed to maintain a specified slump increased with increasing percentages of condensed silica fume; for example, the amount of superplasticizer needed was about 1.0% (by weight of cement + fly ash) for mixtures with 10% fume, and 1.5 to 2.0% for those with 20% fume. In these latter mixtures, the slump loss with time was relatively rapid and the fresh concrete tended to be gluey, specially at lower values of W/(C+F).

The demand for air-entraining admixture was little affected by the addition of up to 10% of condensed silica fume; however, for larger additions, higher quantities of air-entraining admixture were generally necessary to maintain a given air content.

Early-Age Strength Development

All test specimens cast in Series A were tested at ages ranging from 1 to 28 days; the compression tests were performed at 1, 3, 7 and 28 days, and the flexure tests were performed at 7 and 14 days.

Compressive strength at 1 and 3 days - In general, regardless of the W/(C+F), the 1- and 3-day compressive strengths of concrete incorporating condensed silica fume were higher than those of the control concrete (70% portland cement + 30% fly ash), but lower than the strength of the reference concrete (Table 5). There were, nevertheless, a few exceptions such as for concretes with W/(C+F) of 0.60 and 0.50 containing 15 and 20% condensed silica fume respectively; the strengths in these cases were found to equal or slightly exceed the reference values at both 1 and 3 days (Figures 6 and 7).

The substantial gain in strength at early ages of concrete incorporating fly ash and condensed silica fume may suggest an early start of the pozzolanic reaction due to the use of fume, although this may also be partially accounted for by the filler effect of silica fume resulting in a denser matrix structure.

Compressive strength at 7 days - Between the ages of 3 and 7 days, there is indirect evidence of pozzolanic reaction taking place between the condensed silica fume and lime liberated from the hydration of cement, as the gap between the strength of the control and the condensed silica fume concretes widens (Figures 1 to 5). At 7 days, the gains in strength, like the ones at 1 and 3 days, are primarily a function of the percentage of the fume used, though they still show a slight levelling-off trend at lower values of W/(C+F) and higher percentages of the fume used (Table 5). This may be the result of some of the fume not being properly dispersed in the richer mixes. At this age, the addition of a certain amount of silica fume was sufficient to compensate for the loss in strength due to the incorporation of fly ash. The percentage of such addition was 10% for W/(C+F) of 0.40 to 0.60 and increased to 15 and 20% for W/(C+F) of 0.70 and 0.80 respectively (Figure 8). The apparent difference in the efficiency of the condensed silica fume at different W/(C+F) may be due to the fact that the percentage loss in the strength of concrete due to the partial replacement of cement by fly ash was relatively higher for higher values of W/(C+F).

Compressive strength at 28 days - The strength development pattern of the reference and control concretes provides some positive indication of the pozzolanic activity of the fly ash at this stage especially for concretes with lower (W/(C+F) (Figure 1 to 5). However, the difference between the strength of the control and the reference concretes still remains considerable. This is not unusual for concretes incorporating low-calcium fly ashes because their contribution to strength generally becomes significant only after about one month of curing. Notwithstanding the above, the 28-day compressive strength of concretes incorporating condensed silica fume was generally higher than that of the reference concrete, irrespective of the percentage of the fume used, and regardless of the value of W/(C+F) (Figure 9). For the 5% fume addition, the strength gains were somewhat marginal; however, substantial increases were achieved with increasing amounts of the fume. For example, the percentage gain in strength of concrete with a W/(C+F) of 0.60 and incorporating 10 and 20% fume was 32 and 55% respectively. At this age, the larger increases in strength were generally associated with the higher W/(C+F) i.e. 0.60 to 0.80; this is contrary to what was observed at 7 days.

Flexural strength development at 7 and 14 days - The effect of the incorporation of the fume on the flexural strength of concrete was less marked than on the compressive strength. In general, regardless of the W/(C+F) and the silica fume content, the 7-day flexural strengths of concrete prisms incorporating fly ash and silica fume were higher than the strengths of the prisms cast from the control concrete, but were lower than the strength of the reference concrete (Table 5). At 14 days however, the mixtures with 10% or more fume had equal or higher strengths than the reference concretes. The only exception was concrete with a W/(C+F) of 0.80 where the above was true only for concrete with a 20% silica fume addition. These trends at 7 and 14 days are much the same as those observed at 3 and 7 days for the compressive strength.

Strength Development at Later Ages

In series B, the compressive strength of concrete with a W/(C+F) of 0.60 and incorporating various percentages of condensed silica fume was determined at various ages up to 3 months in order to cover both early- and later-age strength development.

The strength results up to 28 days show a pattern similar to that previously observed for concrete with the same W/(C+F) (Figure 10).

At 56 days the strength of the control concrete approached the value reached by the reference concrete; at 91 days the strength of the former concrete slightly exceeds the strength of the latter concrete.

On the other hand, the condensed silica fume concretes show strength increases between 28 and 91 days that are of the same order as that of the control concrete. Since previous investigations (7) have already indicated the contribution of silica fume to strength to be minimal after 28 days, this likely implied that the later-age strength gain due to the pozzolanic activity of fly ash is not impaired by the early-age strength increase due to the use of condensed silica fume. Under the present conditions of investigation, sufficient lime liberated during the hydration of cement appears to be available for the pozzolanic reaction of both the condensed silica fume at early ages and the fly ash at later ages.

CONCLUDING REMARKS

1. The low early-age strength of portland cement concrete incorporating fly ash can be increased by the use of condensed silica fume. The gain in strength is, in general, directly proportional to the percentage of the fume used.

2. At the ages of 7 days and beyond, the loss in compressive strength of concrete due to the incorporation of fly ash can be fully compensated for by a given addition of condensed silica fume. At 7 days, the percentage of such addition ranges from 10% for concretes with W/(C+F) of 0.40, 0.50, and 0.60, to 15 and 20% for concretes with W/(C+F) of 0.70 and 0.80. At 28 days, this percentage is in the order of 5%, regardless of the W/(C+F) of concrete. As for the flexural strength, the above pattern of strength development at 7 days, is reached at 14 days.

3. The continuing increase in strength at 56 and 91 days of the concrete incorporating both fly ash and silica fume indicates the presence of sufficient lime (liberated during the hydration of portland cement) at these ages for the pozzolanic reaction of fly ash to continue.

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TABLE 1 - PHYSICAL PROPERTIES AND CHEMICAL ANALYSES OF CEMENT, FLY ASH, AND CONDENSED SILICA FUME

Description of Test	Portland Cement * (ASTM Type I)	Fly Ash **	Silica ** Fume
Physical tests - general			
Time of set (Vicat needle),			
initial:	2h 04 min	--	--
final:	3h 52 min	--	--
Fineness			
75 μm (passing)	97.0%	--	--
45 μm (passing)	85.9%	86.0 %	--
Surface area, Blaine,	352 m^2/kg	327 m^2/kg	
Surface area, Nitrogen adsorption	--	--	21,000 m^2/kg
Soundness, Autoclave Expansion	0.001 %	--	--
Physical tests - Mortar strength			
Compressive strength of 51-mm cubes at; 3-day	22.7 MPa	--	--
7-day	30.6 MPa	--	--
28-day	39.8 MPa	--	--
Pozzolanic activity index,			
with Portland cement	--	112 %	110 %
with lime	--	6.5 MPa	5.8 MPa
Chemical analysis			
Insoluble residue	0.14%	--	--
Silicon dioxide (SiO_2)	21.54%	53.2	95.17
Aluminum oxide (Al_2O_3)	4.84%	27.0	0.21
Ferric oxide (Fe_2O_3)	2.10%	10.2	0.13
Calcium oxide (CaO), total	64.10%	1.1	0.23
Magnesium oxide (MgO)	2.30%	1.1	0.15
Sulphur trioxide (SO_3)	3.97%	--	0.12
Loss on ignition	0.73%	3.4	2.34
Compound composition			
Tricalcium silicate (C_3S)	50.4 %	--	--
Dicalcium silicate (C_2S)	23.7 %	--	--
Tricalcium aluminate (C_3A)	9.3 %	--	--
Tetracalcium aluminoferrite (C_4AF)	6.4 %	--	--

* Manufacturer's data
** CANMET data

TABLE 2 - MIXTURE PROPORTIONS

Mixture Series	Mixture No.	Type of mixture *	W/C+F **	Relative proportions of cement and fly ash, % by weight		Condensed Silica fume, % by wt of Cement plus Fly Ash	Batch quantities kg/m^3					A.E.A.†, mL/m^3	Superplasticizer, % by weight of Cement plus Fly Ash
				Cement	Fly Ash		Cement	Fly ash	Condensed Silica fume	F.A.	C.A.		
A	1	Reference	0.40	100	0	0	382	0	0	712	1162	170	0
	2	Control		70	30	0	263	113	0	691	1127	600	0
	3	5% Silica fume		70	30	5	263	113	18	683	1115	480	0.33
	4	10%		70	30	10	265	113	39	675	1102	540	0.96
	5	15%		70	30	15	263	113	56	664	1084	600	1.09
	6	20%		70	30	20	262	113	75	653	1066	710	1.50
	7	Reference	0.50	100	0	0	299	0	0	759	1138	80	0
	8	Control		70	30	0	211	91	0	755	1131	450	0
	9	5% Silica fume		70	30	5	209	90	15	747	1114	430	0.30
	10	10%		70	30	10	209	90	30	736	1104	440	1.00
	11	15%		70	30	15	206	88	45	711	1098	640	1.49
	12	20%		70	30	20	208	90	60	718	1076	410	1.47
	13	Reference	0.60	100	0	0	243	0	0	811	1120	90	0
	14	Control		70	30	0	171	74	0	810	1118	300	0
	15	5% Silica fume		70	30	5	172	74	13	806	1114	300	0.43
	16	10%		70	30	10	171	74	24	799	1104	360	0.97
	17	15%		70	30	15	172	74	37	797	1100	420	1.86
	18	20%		70	30	20	172	74	49	788	1090	510	1.84
	19	Reference	0.70	100	0	0	211	0	0	857	1090	90	0
	20	Control		70	30	0	150	64	0	858	1092	320	0
	21	5% Silica fume		70	30	5	149	63	11	851	1083	260	0.47
	22	10%		70	30	10	148	63	21	841	1071	290	0.87
	23	15%		70	30	15	149	63	32	837	1064	350	1.42
	24	20%		70	30	20	149	63	43	832	1058	390	1.79
	25	Reference	0.80	100	0	0	185	0	0	903	1060	70	0
	26	Control		70	30	0	130	56	0	902	1058	230	0
	27	5% Silica fume		70	30	5	131	56	10	905	1062	240	0.57
	28	10%		70	30	10	131	56	18	898	1054	270	0.89
	29	15%		70	30	15	130	55	28	883	1036	290	1.31
	30	20%		70	30	20	130	56	37	878	1031	340	1.60
B	1	Reference	0.60	100	0	0	244	0	0	815	1127	90	0
	2	Control		70	30	0	173	74	0	819	1130	260	0
	3	5% Silica fume		70	30	5	171	73	13	800	1106	290	0.40
	4	10%		70	30	10	170	72	24	793	1096	290	0.95
	5	15%		70	30	15	169	72	36	779	1076	410	2.17
	6	20%		70	30	20	170	72	49	779	1078	470	1.47

* Reference: 100% normal Portland cement
Control: 70% normal Portland cement plus 30% fly ash
Silica fume: 70% normal Portland cement plus 30% fly ash plus additions of condensed silica fume

** Water/ (cement + fly ash) by weight

† Air-entraining admixture

TABLE 3 - PROPERTIES OF FRESH CONCRETE

Mixture Series	Mixture No.	Type of mixture*	W/C+F**	Properties of fresh concrete			
				Temp, °C	Slump, mm	Unit weight, kg/m³	Air content, %
A	1	Reference	0.40	22	40	2409	4.9
	2	Control		22	70	2345	5.6
	3	5% Silica fume		21	65	2345	4.9
	4	10%		22	55	2345	5.2
	5	15%		21	55	2333	5.0
	6	20%		21	75	2320	5.0
	7	Reference	0.50	21	85	2345	6.0
	8	Control		21	90	2339	6.3
	9	5% Silica fume		22	90	2320	6.6
	10	10%		23	85	2320	6.5
	11	15%		22	90	2275	6.8
	12	20%		23	90	2300	6.2
	13	Reference	0.60	21	70	2320	6.3
	14	Control		21	90	2320	5.8
	15	5% Silica fume		20	95	2326	6.1
	16	10%		24	70	2320	6.4
	17	15%		23	70	2326	5.7
	18	20%		22	70	2320	5.6
	19	Reference	0.70	24	65	2307	6.4
	20	Control		23	75	2313	6.2
	21	5% Silica fume		21	85	2307	6.5
	22	10%		21	90	2294	6.5
	23	15%		21	90	2294	6.5
	24	20%		20	90	2294	6.0
	25	Reference	0.80	21	40	2294	6.3
	26	Control		22	95	2294	6.1
	27	5% Silica fume		22	90	2313	6.5
	28	10%		21	75	2307	6.3
	29	15%		21	95	2281	6.6
	30	20%		21	90	2281	6.4
B	1	Reference	0.60	22	65	2333	5.8
	2	Control		22	90	2345	6.0
	3	5% Silica fume		23	80	2307	6.8
	4	10%		24	75	2300	7.0
	5	15%		23	75	2275	7.0
	6	20%		23	55	2294	6.1

* Reference: 100% normal Portland cement
Control: 70% normal Portland cement plus 30% fly ash
Silica fume: 70% normal Portland cement plus 30% fly ash plus additions of condensed silica fume

** Water/ (Cement +fly ash) by weight

TABLE 4 - TESTING SCHEDULE

Mixture Series	Type of Testing	Age of testing						
		1-day	3-day	7-day	14-day	28-day	56-day	91-day
A	Compression (ASTM C 39)	2 cyl.	2 cyl.	2 cyl.		2 cyl.		
	Flexure (ASTM C 78)			3prisms	3prisms			
B	Compression (ASTM C 39)	3 cyl.	3 cyl.	3 cyl.		3 cyl.	3 cyl.	3 cyl.

Note: Series A: size of cylinders - 152 x 305-mm
size of prisms - 76 x 102 x 406-mm

Series B: size of cylinders - 102 x 203-mm

TABLE 5 - COMPRESSIVE AND FLEXURAL STRENGTH TEST RESULTS - SERIES A

W/C+P*	Mix-ture No.	Type of mixture**	Compressive strength of 152x305-mm cylinders, MPa				Flexural strength of 76x102x406-mm prisms, MPa	
			1-day	3-day	7-day	28-day	7-day	14-day
0.40	1	Reference	21.8	30.8	33.5	40.1	5.8	6.4
	2	Control	11.0	18.1	24.2	33.7	4.2	5.0
	3	5% Silica fume	11.2	22.2	28.5	40.4	5.0	5.4
	4	10%	15.6	25.7	35.3	46.8	5.4	6.8
	5	15%	16.2	27.4	39.1	49.0	5.3	6.6
	6	20%	16.4	28.8	41.0	53.0	6.1	6.9
0.50	7	Reference	10.7	20.1	25.5	32.0	4.6	4.9
	8	Control	5.8	12.6	17.7	26.3	3.6	4.1
	9	5% Silica fume	5.9	13.7	19.7	30.6	3.8	4.3
	10	10%	9.5	17.8	27.1	37.6	4.3	5.0
	11	15%	9.3	17.7	29.1	41.5	4.0	4.9
	12	20%	10.9	20.1	31.7	46.5	4.6	6.2
0.60	13	Reference	6.3	13.0	18.6	23.5	3.9	4.3
	14	Control	3.4	8.3	12.4	18.5	3.0	3.7
	15	5% Silica fume	3.7	9.5	14.8	27.0	3.3	4.4
	16	10%	6.0	12.6	18.4	31.0	3.5	4.2
	17	15%	6.9	14.4	22.5	34.3	3.6	4.3
	18	20%	7.0	13.6	24.4	36.6	3.8	4.9
0.70	19	Reference	5.3	10.7	14.6	19.3	3.1	3.5
	20	Control	2.6	6.1	8.5	13.3	2.1	2.8
	21	5% Silica fume	2.3	6.5	10.6	20.4	2.2	3.1
	22	10%	2.8	7.5	12.8	24.3	2.5	3.6
	23	15%	3.4	8.1	14.5	27.5	2.5	3.7
	24	20%	3.8	9.5	18.7	32.4	3.1	4.7
0.80	25	Reference	3.5	7.8	11.5	15.7	2.8	3.4
	26	Control	1.5	4.1	6.3	10.1	1.6	2.3
	27	5% Silica fume	1.8	5.1	8.4	16.6	2.1	2.8
	28	10%	2.1	5.4	9.3	19.6	2.0	2.9
	29	15%	2.4	5.9	10.7	21.7	2.3	3.2
	30	20%	2.7	6.3	12.6	22.8	2.4	3.5

* Water / (cement + fly ash) by weight

** Reference: 100% normal Portland cement

Control : 70% normal Portland cement plus 30% fly ash

Silica Fume: 70% normal Portland cement plus 30% fly ash plus additions of condensed silica fume

Note: Each value is average of two tests for compressive strength and three tests for flexural strength.

TABLE 6 - COMPRESSIVE STRENGTH TEST RESULTS - SERIES B

W/C+F*	Mix-ture No.	Type of mixture**	Compressive strength of 102x203-mm cylinders, MPa					
			1-day	3-day	7-day	28-day	56-day	91-day
0.60	1	Reference	6.2	12.2	16.1	21.4	22.6	23.9
	2	Control	3.2	7.8	11.1	18.1	21.7	24.3
	3	5% Silica fume	4.0	9.6	14.7	23.5	27.5	29.0
	4	10%	4.3	11.2	18.1	29.4	31.9	35.2
	5	15%	5.1	11.8	21.9	31.4	35.1	36.4
	6	20%	6.3	13.3	22.2	30.5	36.3	37.8

* Water/ (cement + fly ash) by weight
** Reference: 100% normal Portland cement
Control : 70% normal Portland cement plus 30% fly ash
Silica fume: 70% normal Portland cement plus 30% fly ash plus additions of condensed silica fume

Note: Each value is average of 3 tests

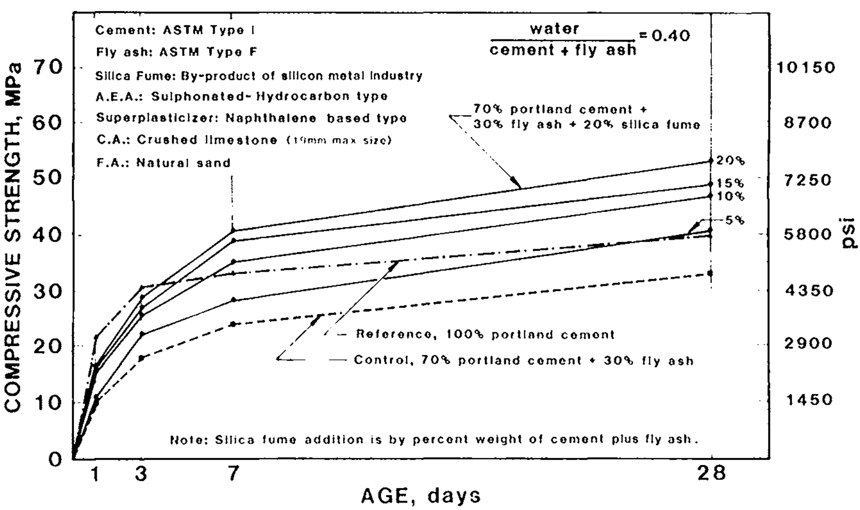

Fig. 1--Compressive strength versus age for concrete with a W/(C+F) of 0.40

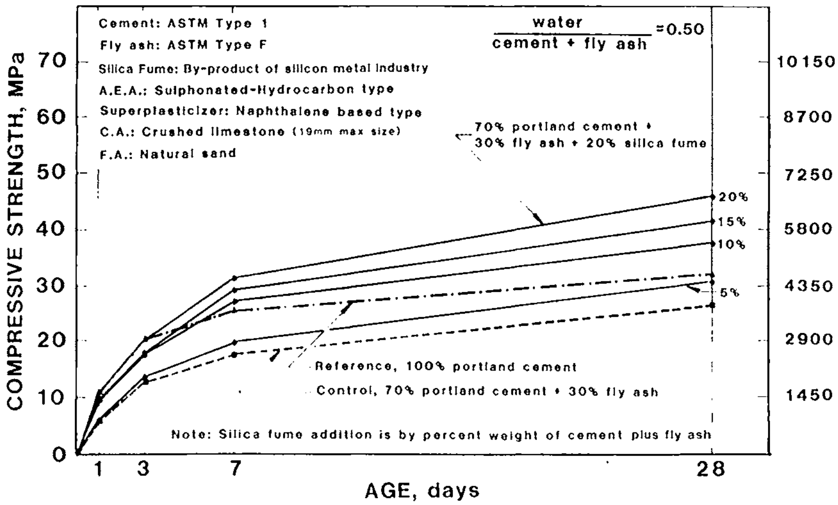

Fig. 2--Compressive strength versus age for concrete with a W/(C+F) of 0.50

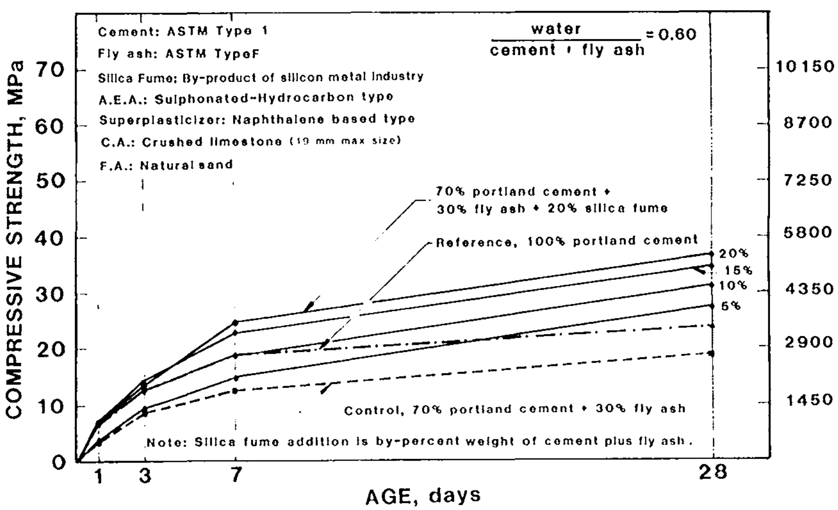

Fig. 3--Compressive strength versus age for concrete with a W/(C+F) of 0.60

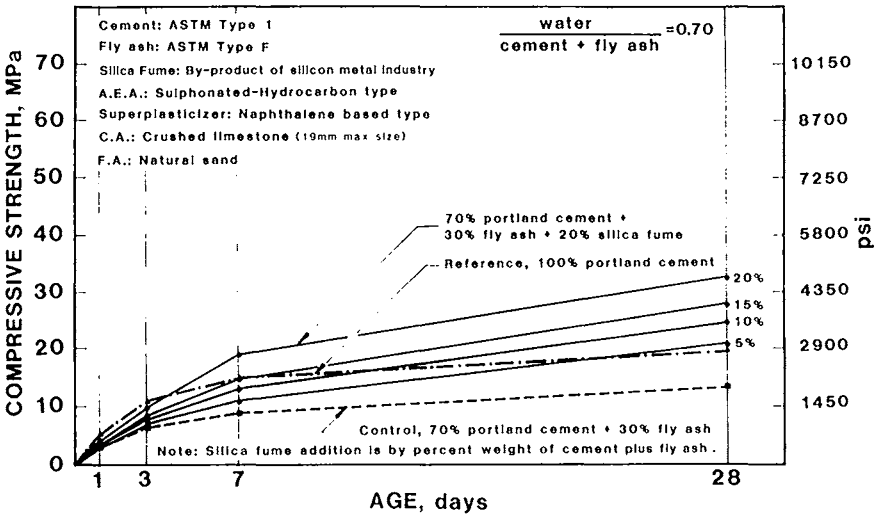

Fig. 4--Compressive strength versus age for concrete with a W/(C+F) of 0.70

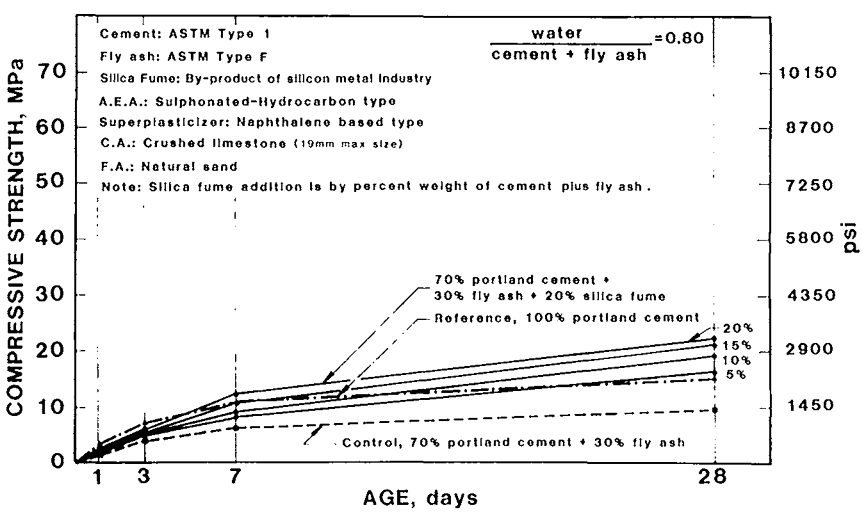

Fig. 5--Compressive strength versus age for concrete with a W/(C+F) of 0.80

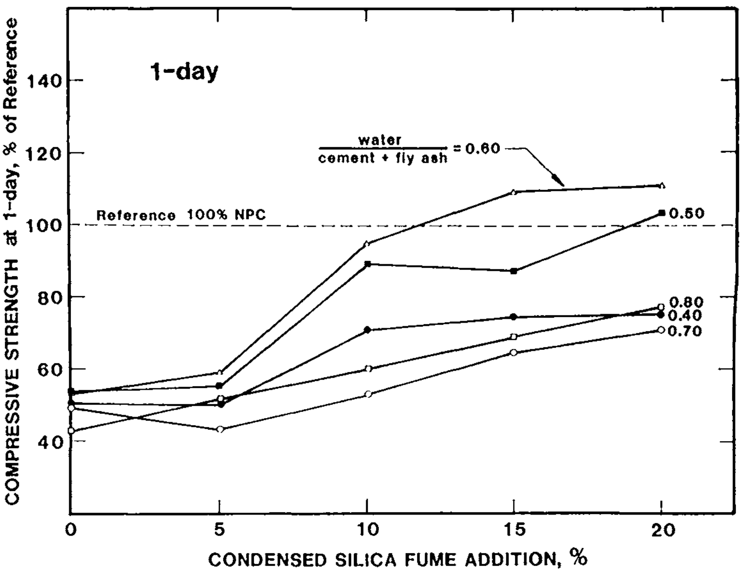

Fig. 6--Comparison between compressive strengths of the reference and silica fume concretes at 1 day

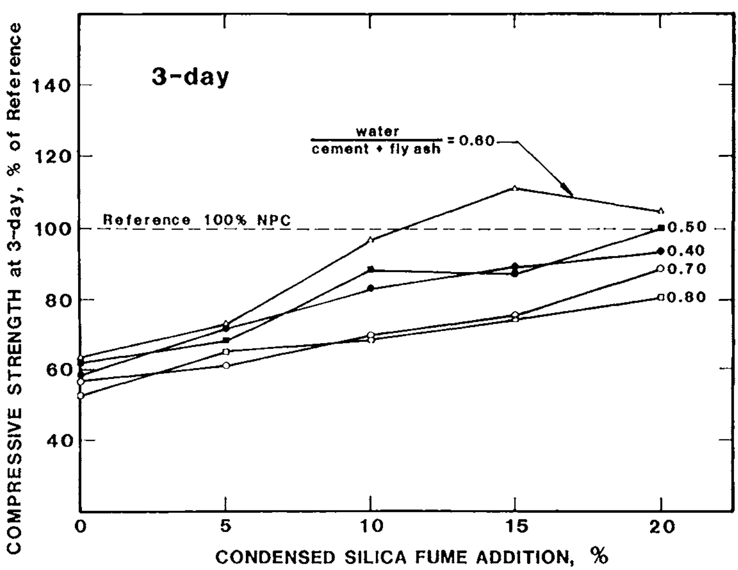

Fig. 7--Comparison between compressive strengths of the reference and silica fume concretes at 3 days

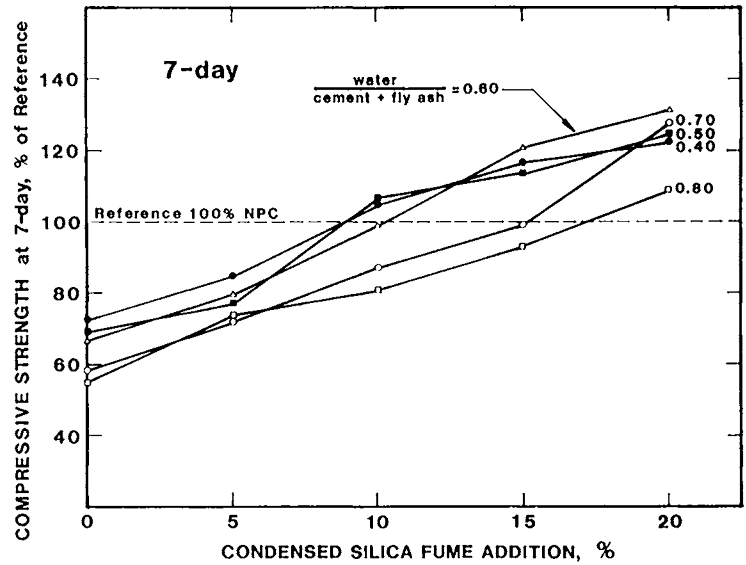

Fig. 8--Comparison between compressive strengths of the reference and silica fume concretes at 7 days

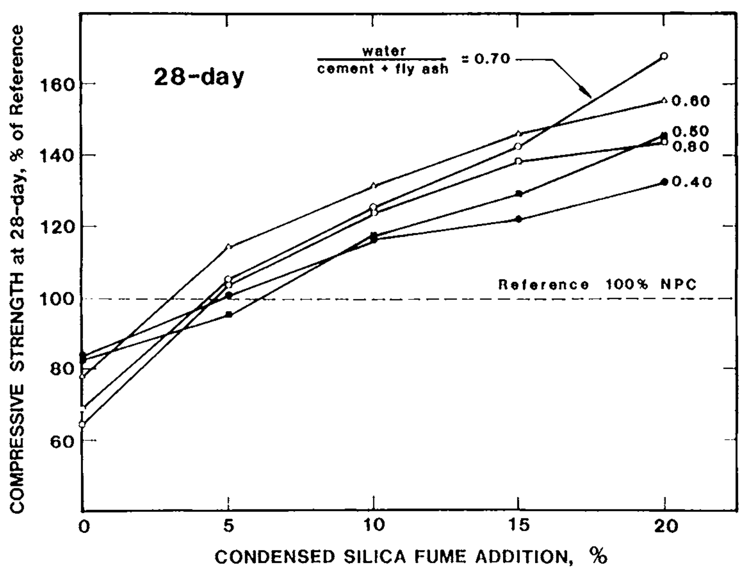

Fig. 9--Comparison between compressive strengths of the reference and silica fume concretes at 28 days

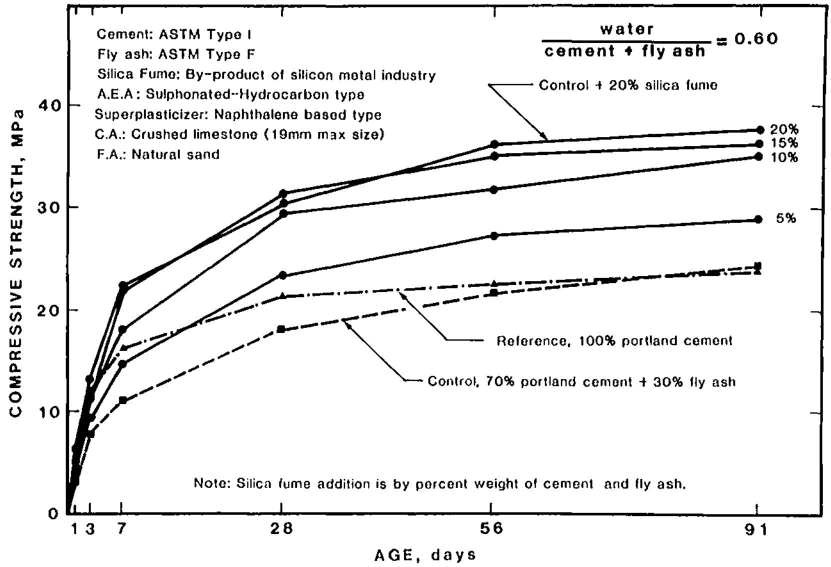

Fig. 10--Compressive strength development of concrete with a W/(C+F) of 0.60