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SILICA FUME IN CONCRETE - PRELIMINARY INVESTIGATION

G.G. CARETTE AND V.M. MALHOTRA

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SILICA FUME IN CONCRETE - PRELIMINARY INVESTIGATION

by

G.G. Carette* and V.M. Malhotra**

SUMMARY

Portland cement is a highly energy intensive material and therefore considerable effort is being made to find substitutes for partially replacing cement in concrete. Silica fume, a byproduct in the manufacture of ferro-silicon and silicon metal is one possible substitute. Results are given of a preliminary investigation to determine the strength, freezing and thawing characteristics and drying shrinkage of concrete incorporating various percentages of silica fume.

Eighteen 0.06 m^3 air-entrained concrete mixes were made incorporating 0 to 30% silica fume as a partial replacement for cement. Some mixes were proportioned to have constant slump with water-to-cementitious materials ratios (W:C+S) ranging from 0.64 to 0.84, whereas others were proportioned to have a constant W:C+S ratio of 0.40; the latter incorporated a superplasticizer. Cylinder and prism specimens were cast for determining the mechanical properties and durability of concrete.

Test data indicate that silica fume, when used in concrete as a partial replacement for cement, performs as a highly efficient pozzolanic material. Notwithstanding the extreme fineness of silica fume (20 000 m^2/kg) thus its high water demand, the compressive strength of constant slump concrete incorporating up to 30% silica fume is comparable with or higher than the strength of control concrete.

Superplasticized concrete mixes having a W:C+S ratio maintained at 0.40 indicate some increase in compressive strength at all ages regardless of the percentage of silica fume.

Concrete prisms incorporating 0 to 15% silica fume (W:C+S = 0.40) perform satisfactorily when subjected to 300 cycles of freezing and thawing; however, prisms incorporating 20 to 30% silica fume and large dosages of superplasticizer show excessive expansion and relatively low dynamic moduli after 300 cycles.

The drying shrinkage of concrete incorporating silica fume is generally comparable with that of control concrete regardless of the W:C+S ratio.

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*Materials engineer and **Head, Construction Materials Section, Mineral Sciences Laboratories, CANMET, Energy, Mines and Resources Canada, Ottawa.

UTILISATION DE LA POUSSIÈRE DE SILICE DANS LE BÉTON - EXAMENS PRÉLIMINAIRES

par

G.G. Carette* et V.M. Malhotra**

SOMMAIRE

Le ciment portland étant un matériau nécessitant un grand apport d'énergie lors de sa fabrication, on s'efforce grandement de trouver des substituts afin de le remplacer partiellement dans le béton. La poussière de silice, un dérivé de la fabrication du silicium et du ferrosilicium, s'avère un substitut possible. Ce rapport contient les résultats d'essais préliminaires effectués pour déterminer la résistance, les caractéristiques de gel et de dégel, ainsi que le retrait dû au séchage du béton incorporant divers pourcentages de poussière de silice.

Dix-huit mélanges de béton à air-occlus ont été préparés en incorporant de 0 à 30% de poussière de silice comme remplacement partiel du ciment. Certains mélanges étaient proportionnés de façon à avoir un affaissement constant et un rapport eau-matériaux cimentaires (W:C+S) variant de 0,64 à 0,84 tandis que d'autres étaient proportionnés selon un rapport W:C+S constant de 0,40; ces derniers mélanges incorporaient un superplastifiant. Pour chaque mélange, des échantillons cylindriques et prismatiques ont été fabriqués afin de procéder à la détermination des propriétés mécaniques et de la durabilité du béton.

Les résultats d'essais indiquent que la poussière de silice, lorsqu'employée comme remplacement partiel du ciment dans le béton, s'avère une pouzzolane très efficace. Malgré l'extrême finesse de la poussière de silice, (20 000 m^2/kg), d'où son grand besoin en eau, la résistance à la compression des bétons ayant un affaissement constant et contenant jusqu'à 30% de poussière de silice est comparable ou plus élevée que celle des bétons témoins.

En ce qui a trait aux mélanges de béton superplastifiés ayant un rapport W:C+S de 0,40, tout porte à croire qu'il y a un accroissement de la résistance à la compression à tous les stages de vieillissement indépendamment du pourcentage de poussière de silice utilisé.

Les prismes de béton comportant de 0 à 15% de poussière de silice (W:C+S = 0,40) donnent de bons rendements lorsque soumis à 300 cycles de gel-dégel; cependant, les prismes comportant de 20 à 30% de poussière de silice et de grandes quantités de superplastifiant font preuve d'expansion excessive et présentent un module d'élasticité dynamique relativement bas après 300 cycles.

Le retrait dû au séchage des bétons composés de poussière de silice est généralement comparable à celui des bétons témoins indépendamment du rapport W:C+S.

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*Ingénieur et **Chef, Section des matériaux de construction, Laboratoires des sciences minérales, CANMET, Energie, Mines et Ressources Canada, Ottawa.

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INTRODUCTION

In recent years, CANMET has become increasingly involved in research aimed at energy conservation in the cement and concrete industry. This, in part, is being accomplished by encouraging the use of less energy intensive cementitious materials such as fly ash, slags and pozzolans in concrete (1-6). Lately, some attention has been given to the use of condensed silica fume as a possible partial replacement for cement. Until recently, because of problems associated with the extreme fineness of the material and its high water requirement when mixed with portland cement, its use in concrete was confined to specialized applications. However, the availability of superplasticizers has opened up new possibilities for its use.

Investigations on silica fume in concrete have been going on in Scandinavian countries, particularly in Norway and Denmark where the material has been used on a limited scale since 1976 (7,8). In North America, only limited data have been reported to date (9,10).

This report briefly describes the physical and chemical properties of silica fume and gives results of a preliminary laboratory investigation to determine the mechanical properties and resistance to freezing and thawing of concrete incorporating this material.

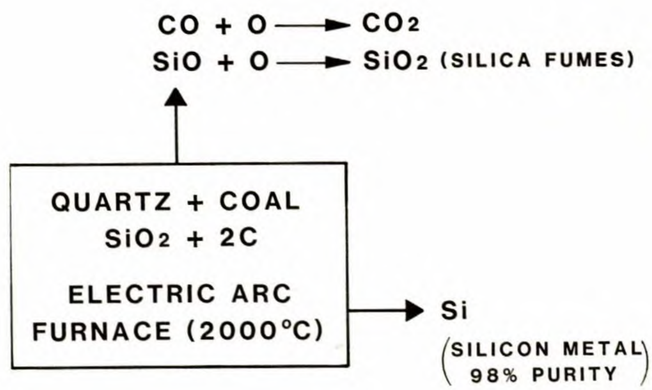

Fig. 1 - Simplified sketch showing silica fume as a byproduct in the production of silicon metal

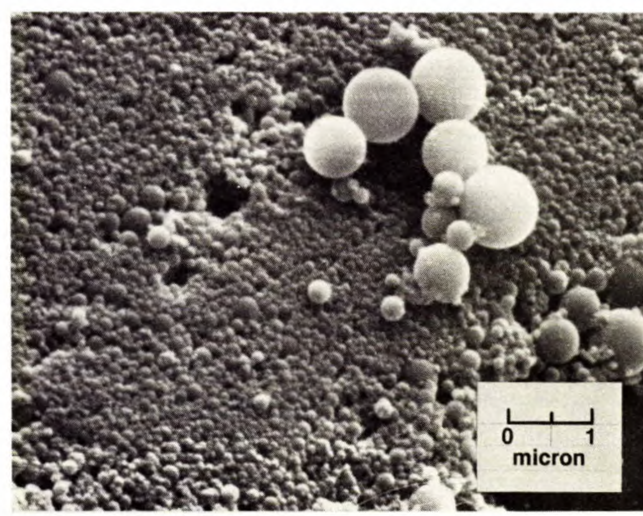

Fig. 2 - SEM micrograph of silica fume from a Canadian plant

SILICA FUME

Silica fume is a byproduct resulting from the reduction of high purity quartz with coal in electric arc furnaces in the manufacture of ferro-silicon and silicon metal (Fig. 1). The fume, which has a high content of amorphous silicon dioxide and consists of very fine spherical particles is collected by filtering gases escaping from the furnaces (Fig. 2).

CHEMICAL COMPOSITION

Table 1 gives chemical compositions of typical silica fumes from silicon furnaces in Norway and Canada. The fumes generally are more than 90% silicon dioxide, most of which is in an amorphous form. The chemical composition of the fumes varies according to the type of alloy or metal being produced. For example, the fumes from a ferro-silicon furnace generally contain more iron and magnesium than those from a silicon furnace.

FINENESS

Silica fume consists of very fine vitreous particles and has a specific surface area of the order of 20 000 m^2/kg. Its extreme fineness

Table 1 - Chemical composition of silica fumes from silicon furnaces in Norway and Canada

Constituent, %	Norway*	Canada**
SiO_2	90.0 - 96.0	93.7
Al_2O_3	0.5 - 3.0	0.3
Fe_2O_3	0.2 - 0.8	0.8
MgO	0.5 - 1.5	0.2
CaO	0.1 - 0.5	0.2
Na_2O	0.2 - 0.7	0.2
K_2O	0.4 - 1.0	0.5
C	0.5 - 1.4	2.6
S	0.1 - 0.4	0.1
LOI	0.7 - 2.5	2.8

*From brochure Elkem Silica, Elkem - Spigerverket A/S, Norway

**From a plant in Quebec, Canada

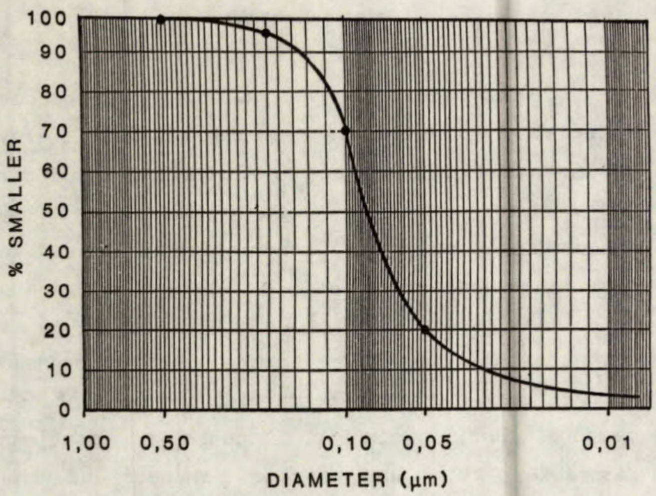

Fig. 3 - Particle size distribution of silica fume from a Canadian plant

is best illustrated by the following comparison with other fine materials:

Silica fume	:	~20 000 m^2/kg
Tobacco smoke	:	~10 000 m^2/kg
Fly ash	:	400 to 700 m^2/kg
Normal portland cement	:	300 to 400 m^2/kg

The particle size distribution of a silica fume from Canada shows most particles to be smaller than 1 μm and have an average diameter of about 0.1 μm (Fig. 3).

The high reactivity of silica fume with Portland cement is primarily due to its very high specific surface and high content of amorphous silicon dioxide.

OUTPUT OF SILICA FUME

Exact data on the annual output of silica fume in Canada and the U.S.A. are unavailable however, estimates indicate about 20 000 tonnes was available in Canada in 1981. The corresponding figure for the U.S.A. is of the order of 300 000 tonnes.

Norway is one of the world's largest producers of silica fume where an estimated 120 000 tonnes is produced annually; this is expected to double over the next several years. Total world production is estimated at about 1 x 10^6 tonnes.

SCOPE OF INVESTIGATION

In this preliminary investigation, a total of 18 concrete mixes were made to evaluate the performance of silica fume in portland cement concrete. The program was divided into three series.

(1) Series A (constant slump) - To determine the strength development and drying shrinkage of concrete made with initial water-to-cement ratio of 0.64, and up to 30% replacement of cement by silica fume. The slump of the concrete was kept constant by increasing the water content with increasing amounts of silica fume.

(2) Series B (constant water-to-cementitious materials ratio) - To determine the 28-day compressive strength, drying shrinkage and resistance to freezing and thawing of concrete made with a constant water-to-cementitious materials ratio of 0.40, and up to 30% replacement of cement by silica fume. The

above ratio was kept constant by using a superplasticizer to compensate for the loss of workability due to increasing amounts of silica fume.

(3) Series C - To determine the compressive strength development with age of concrete mixes having proportions identical to those in Series B.

MATERIALS

The concrete mixes were made in the CANMET laboratory between May and July 1981 using the following materials.

CEMENT

Normal portland cement, CSA type 10, was used. Its physical properties and chemical analysis are given in Table 2.

SILICA FUME

Silica fume from a Canadian source was used as a partial replacement for cement. Its physical properties and chemical analysis are given in Table 2.

AGGREGATES

Minus 19-mm crushed limestone and natural sand were used as the coarse and fine aggregates respectively. To keep the grading uniform for each mix, both aggregates were separated into different size fractions which were then recombined to a specific grading.

The specific gravity 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% aqueous solution having a density of 1200 kg/m^3. The chloride content is negligible.

AIR-ENTRAINING AGENT

A sulphonated hydrocarbon type air-entraining agent (AEA) was used.

CONCRETE MIXES

Mix proportions are summarized in Table 3. The room-dry coarse and fine aggregates were soaked for 24 h before mixing and the amount of water was subsequently adjusted according to the water absorbed. Concretes were mixed in a laboratory counter current mixer for 6 min except those incorporating superplasticizers or relatively large amounts of silica fume for which the time was extended up to 12 min.

Three series of concrete mixes were made. In Series A, the slump of the concrete was maintained constant at 75 ± 10 mm and had an air content of 6.5 ± 1%. The initial mix in this series had a W:C+S* ratio of 0.64 and silica fume content of 0%. The water demand increased with increasing amounts of silica fume and at 30% replacement the W:C+S ratio reached 0.84.

In Series B, the W:C+S ratio was kept constant at 0.40. The decrease in workability due to increasing amounts of silica fume was compensated for by adding a superplasticizer. Its dosage was adjusted to give a slump in the order of 75 mm; the mixes with higher amounts of silica fume were superplasticized to give higher slumps. Difficulty was experienced to entrain large quantities of air in the concrete mixes containing high percentages of silica fume. Therefore, air contents from 3.8 to 5.1% were accepted for this series.

Series C proportions were basically identical to those of Series B. An attempt was made to improve the entrained air contents obtained in Series B. This was partly achieved by changing mixing procedures. However, even then, it was impossible to entrain more than 4.1% air in a mix incorporating 30% silica fume.

The properties of fresh concrete in the above three series are given in Table 4.

CASTING AND CURING OF TEST SPECIMENS

SERIES A

Twenty-one 102 x 203-mm cylinders and six

*Water:(cement + silica fume) ratio

Table 2 - Physical properties and chemical analysis of cement and silica fume

Description of test	Portland cement*	Silica fume**
Physical tests		
Fineness		
passing 75-µm sieve	97.0%	-
passing 45-µm sieve	85.9%	-
surface area, Blaine	352 m^2/kg	-
surface area, nitrogen adsorption	-	21 000 m^2/kg
Compressive strength of 51-mm mortar cubes,		
at 3-day	22.7 MPa	-
7-day	30.6 MPa	-
28-day	39.8 MPa	-
Pozzolanic activity index,		
with portland cement	-	110%
with lime	-	5.8 MPa
Chemical tests		
SiO_2	21.54%	95.17%
CaO (total)	64.10%	0.23%
LOI	0.73%	2.34%
Insoluble	0.14%	-
SO_3	3.97%	0.12%
MgO	2.30%	0.15%
Fe_2O_3	2.10%	0.13%
Al_2O_3	4.84%	0.21%
Na_2O	-	0.10%
K_2O	-	0.27%
C	-	1.56%
Compound composition,		
C_3S	50.4%	-
C_2S	23.7%	-
C_3A	9.3%	-
C_4AF	6.4%	-

*Manufacturer's data

**CANMET data

Table 3 - Mix proportions

Series	Mix No.	Replacement of cement by silica fume, %	W:C+S ratio*	A:C+S ratio**	Quantities, kg/m³ Cement (C)	Silica fume (S)	A.E.A., mL/m³***	SP+, % by weight of (C+S)
A	1	0	0.64	8.02	233	0	110	0
	2	5	0.65	8.01	220	12	110	0
	3	10	0.69	7.97	209	24	110	0
	4	15	0.73	7.92	199	35	110	0
	5	20	0.77	7.87	184	46	150	0
	6	30	0.84	7.57	162	70	220	0
B	7	0	0.40	4.43	400	0	170	0
	8	5	0.40	4.42	381	20	190	0.1
	9	10	0.40	4.40	367	41	240	0.8
	10	15	0.40	4.38	342	61	540	1.0
	11	20	0.40	4.37	322	81	770	1.9
	12	30	0.40	4.33	285	122	1090	2.7
C	13	0	0.40	4.43	404	0	170	0
	14	5	0.40	4.42	386	21	230	0.3
	15	10	0.40	4.41	358	40	530	0.8
	16	15	0.40	4.39	340	60	690	1.5
	17	20	0.40	4.37	320	80	920	1.6
	18	30	0.40	4.33	284	122	1240	2.1

*Water:(cement + silica fume) ratio (by weight)

**Aggregate:(cement + silica fume) ratio (by weight)

***Air-entraining agent

+Superplasticizer

76 x 102 x 406-mm prisms were cast from each mix. Both cylinder and prism specimens 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. The cylinders and four of the prisms used for freezing and thawing tests were placed in a moist-curing room until required for testing; the remaining two prisms used for drying shrinkage were placed in a water tank.

SERIES B

Two 152 x 305-mm cylinders and six 76 x 102 x 406-mm prisms were cast from each mix. The test specimens were cast and cured in the same manner as Series A except compaction of the cylinders was done by internal vibration.

SERIES C

Eight 152 x 305-mm cylinders were prepared from each mix; the casting and curing procedures were identical to those for similar specimens in Series B.

Table 4 - Properties of fresh concrete

Series	Mix No.	Type	W:C+S ratio*	Properties of fresh concrete Temp, °C	Slump, mm	Unit weight, kg/m^3	Air content, %
A	1	control	0.64	21	75	2250	6.2
	2	5% silica fume	0.65	23	80	2240	7.2
	3	10% silica fume	0.69	21	65	2240	6.6
	4	15% silica fume	0.73	21	75	2260	5.8
	5	20% silica fume	0.77	21	80	2220	6.0
	6	30% silica fume	0.84	21	75	2190	5.9
B	7	control	0.40	21	75	2340	5.1
	8	5% silica fume + SP	0.40	23	65	2330	4.4
	9	10% silica fume + SP	0.40	22	60	2370	3.8
	10	15% silica fume + SP	0.40	22	75	2330	4.5
	11	20% silica fume + SP	0.40	24	180**	2330	4.6
	12	30% silica fume + SP	0.40	23	160**	2340	4.2
C	13	control	0.40	20	80	2360	5.5
	14	5% silica fume + SP	0.40	21	80	2370	5.0
	15	10% silica fume + SP	0.40	22	80	2320	6.4
	16	15% silica fume + SP	0.40	23	75	2320	5.9
	17	20% silica fume + SP	0.40	22	110	2320	5.5
	18	30% silica fume + SP	0.40	22	100	2330	4.1

*Water:(cement + silica fume) ratio (by weight)

**Increased slumps in Series B (No. 11 and 12) are due to the increased dosage of the superplasticizer

TESTING OF SPECIMENS

The specimens were tested in compression, flexure and splitting-tension at various ages in accordance with the testing schedule shown in Table 5. Before compression testing, specimens were capped with a sulphur and flint mixture. As far as possible, all tests were made according to ASTM standards.

Freezing and thawing tests were done in accordance with ASTM Standard C666, Procedure A: freezing in water and thawing in water. The freezing and thawing unit performed 8 cycles per day. The test specimens were examined after every 50-cycle interval. Length, weight, resonant frequency and pulse velocity were determined every 100 cycles. The freezing and thawing tests were terminated after a minimum of 500 cycles unless the test prisms had failed earlier. Following this, both the reference and test prisms were tested in flexure.

For drying shrinkage tests, the specimens were cured in lime-saturated water for 28 days after which they were stored in air at a relative humidity of 50 ± 4% and a temperature of 23 ± 1°C. Length and weight changes were recorded over an 84-day period.

Table 5 - Testing schedule

Series	Type of testing	Age of testing 1-day	3-day	7-day	14-day	28-day	91-day
A	Compression (ASTM C39-72)	3 cyl.	3 cyl.	3 cyl.	--	3 cyl.	3 cyl.
	Flexure (ASTM C78-75)	--	--	--	2 prisms	2 prisms	--
	Splitting-tension (ASTM C496-71)	--	--	3 cyl.	--	3 cyl.	--
	Drying shrinkage (ASTM C157-75)	Two prisms were exposed to air-drying at 23°C and 50% R.H. at the end of 28 days of curing in water.					
B	Compression (ASTM C39-72)	--	--	--	--	2 cyl.	--
	Freezing and thawing (ASTM C666-77 - Procedure A)	Two prisms were exposed to repeated cycles of freezing and thawing at the end of 14 days of moist curing. Two companion prisms were kept in moist-curing room for reference purposes.					
	Drying shrinkage (ASTM C157-75)	Same as Series A.					
C	Compression (ASTM C39-72)	2 cyl.	--	2 cyl.	--	2 cyl.	2 cyl.

TEST RESULTS

Test results showing the increased water requirement with increasing amounts of silica fume in Series A are plotted in Fig. 4. A summary of the strengths obtained in all series is given in Tables 6 and 7 and the data are illustrated in Fig. 5 to 9.

The results of freezing and thawing tests performed in Series B are shown in Table 8 and 9 and Fig. 10 and 11. Data on the drying shrinkage of concrete from both Series A and B are given in Table 10 and plotted in Fig. 12 to 14.

DISCUSSION OF TEST RESULTS

COLOUR

Fresh and hardened concrete incorporating silica fume is dark grey compared with the grey colour of conventional concrete. This is particularly so for concretes incorporating higher percentages of silica fume.

WATER REQUIREMENT

Series A - Constant Slump

In Series A, the water demand increased almost linearly with increasing amounts of silica fume (Fig. 4). For example, at 30% replacement, the water demand increased by almost 30%. This was probably due to the very high surface area of silica fume (21 000 m^2/kg) compared with that of cement (350 m^2/kg). Examination and handling of the fresh concrete indicated that at constant slump, there was little change in workability regardless of the amount of silica fume.

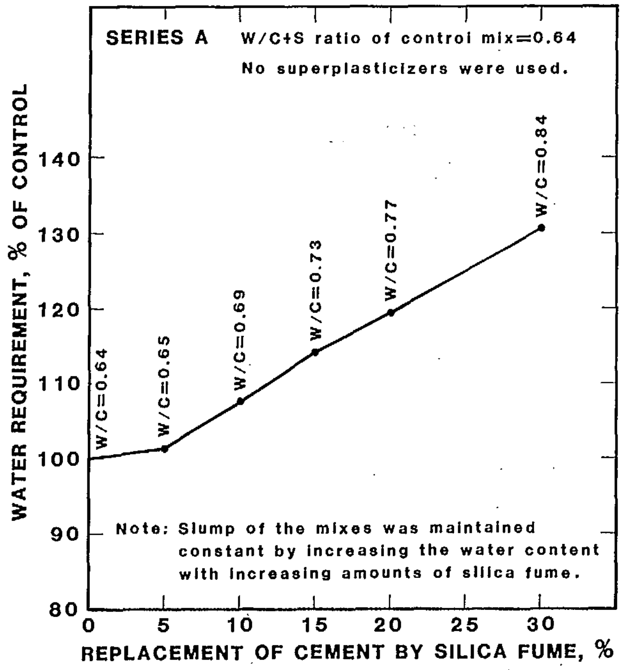

Fig. 4 - Water requirement versus silica fume content - Series A

Series B and C - Constant W:C+S Ratio

In the above, the W:C+S ratio was kept constant and the slump loss due to incorporating silica fume was compensated for by adding a superplasticizer. At lower replacements of cement by silica fume, sufficient superplasticizer was added to maintain a slump of about 75 mm; at higher replacements, large amounts of superplasticizer were added to obtain higher slumps to allow sufficient time for casting of the specimens because of rapid slump loss. The rapid loss of slump in concrete mixes incorporating higher amounts of silica fume presented a problem which requires further research.

AIR-ENTRAINING AGENT DOSAGE

The dosage of an air-entraining agent to produce the required volume of air increased markedly with increasing amounts of silica fume except for Series A mixes containing less than 15% silica fume. For example, in Series B, the dosage increased from 170 mL/m^3 for the control mix to 1090 mL/m^3 for that incorporating 30% silica fume replacement. Despite the latter increased dosage, the volume of entrained air did not exceed 4.2% compared with 5.1% for the control mix.

The increased demand for an air-entraining agent with increasing amounts of silica fume is probably due, again, to its very high surface area and possibly to the presence of carbon.

MIXING AND CASTING OF TEST SPECIMENS

As the silica fume content of the mixes increased, longer mixing times were required to achieve proper dispersion of fine materials. In Series B and C, where relatively large volumes of silica fume were added, flocculation of the fines during mixing was mostly overcome by adding large dosages of superplasticizer. These large dosages together with high percentages of silica fume resulted in concrete having a gluey consistency. This, combined with subsequent rapid loss of slump, necessitated more intensive vibration in order to achieve proper compaction of the test specimens.

COMPRESSIVE STRENGTH

Series A - Constant Slump

Since slump of the concrete mixes was kept constant, the water demand, and hence the W:C+S ratio of the concrete increased with increasing amounts of silica fume.

At 1 day, the strength of concretes incorporating silica fume was considerably lower than that of the control specimens; the decrease in strength increased with increasing percentages of silica fume (Fig. 5 and 6). However, for silica fume contents of 5 to 15%, the compressive strength of test specimens at 3 days and beyond was generally higher than that of control specimens. For example, the 91-day strength of concrete cylinders incorporating 15% silica fume was 28.4 MPa compared with 24.8 MPa for the control specimens, keeping in mind that W:C+S ratio of the former was 0.73 compared with 0.64 for the latter. The strength of concrete cylinders incorporating 20% silica fume was generally lower than that of

Table 6 - Compressive, flexural and splitting-tensile strength test results at various ages - Series A

				Compressive strength of 102 x 203-mm cylinders, MPa					Flexural strength of 76 x 102 x 406-mm prisms, MPa		Splitting-tensile strength of 102 x 203-mm cylinders, MPa	
Series	Mix No.	Type	W:C+S ratio*	1-day	3-day	7-day	28-day	91-day	14-day	28-day	7-day	28-day
A	1	control	0.64	9.8	14.1	18.0	21.7	24.8	4.5	4.6	2.7	3.2
	2	5% silica fume	0.65	9.0	14.3	19.9	26.4	29.3	5.3	5.4	2.7	3.4
	3	10% silica fume	0.69	8.3	14.2	20.6	26.7	30.5	4.7	5.2	2.8	3.6
	4	15% silica fume	0.73	6.7	13.2	18.3	27.6	28.4	4.5	5.0	2.8	3.3
	5	20% silica fume	0.77	5.0	10.4	15.5	23.0	25.4	4.3	4.5	2.5	3.3
	6	30% silica fume	0.84	4.4	8.1	14.1	21.4	25.3	3.7	4.5	2.2	2.8

*Water:(cement + silica fume) ratio (by weight)

Note: Each compressive and splitting-tensile strength value is average of 3 tests.
Each flexural strength value is average of 2 tests.

Table 7 - Compressive strength test results - Series B and C

				Compressive strength of 152 x 305-mm cylinders, MPa			
Series	Mix No.	Type	W:C+S ratio*	1-day	7-day	28-day	91-day
B	7	control	0.40	-	-	39.6	-
	8	5% silica fume + SP	0.40	-	-	45.0	-
	9	10% silica fume + SP	0.40	-	-	45.1	-
	10	15% silica fume + SP	0.40	-	-	43.4	-
	11	20% silica fume + SP	0.40	-	-	45.1	-
	12	30% silica fume + SP	0.40	-	-	49.9	-
C	13	control	0.40	22.6	31.2	38.4	43.7
	14	5% silica fume + SP	0.40	25.9	33.6	44.7	48.3
	15	10% silica fume + SP	0.40	25.2	33.5	44.1	45.1
	16	15% silica fume + SP	0.40	23.9	35.7	43.7	43.3
	17	20% silica fume + SP	0.40	26.1	38.4	43.0	49.4
	18	30% silica fume + SP	0.40	24.8	40.8	50.9	60.9

*Water:(cement + silica fume) ratio (by weight)

control cylinders up to 20 days; beyond this, the reverse was true (Fig. 6). For 30% silica fume, this reversal did not take place until 91 days (Fig. 5).

The above strength development pattern of concrete incorporating silica fume is similar to that of concrete incorporating fly ash and slag with the important exception that silica fume appears to be a more efficient pozzolanic material (3).

Series B and C - Constant W:C+S Ratio

In these series, the W:C+S ratio was kept constant at 0.40 and the loss in slump due to increasing silica fume content was compensated for by adding a superplasticizer. Test data indicate that regardless of the age and percentage of silica fume used, the compressive strength of test cylinders incorporating silica fume was somewhat higher than that of control cylinders (Fig. 7 and 8).

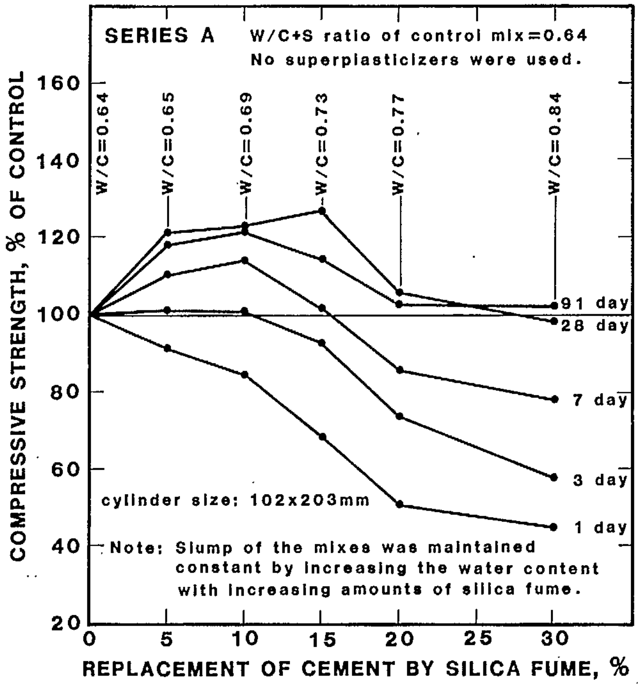

Fig. 5 - Effect of replacement of cement by silica fume on compressive strength - Series A

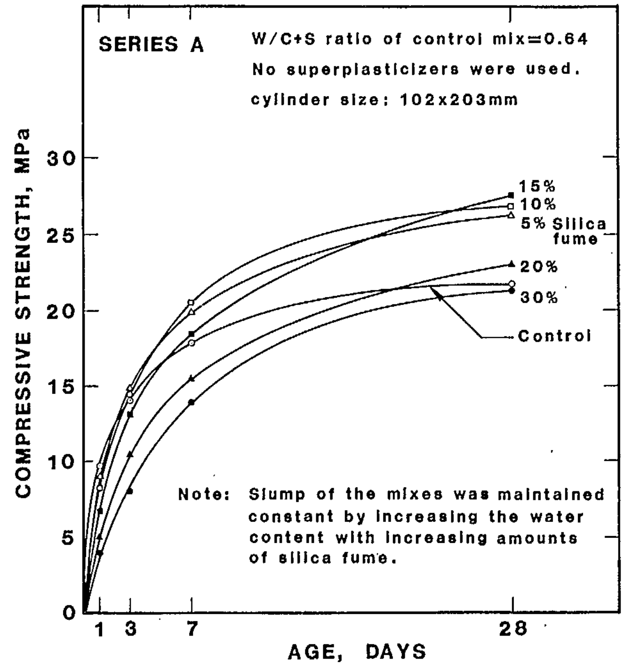

Fig. 6 - Age versus compressive strength - Series A

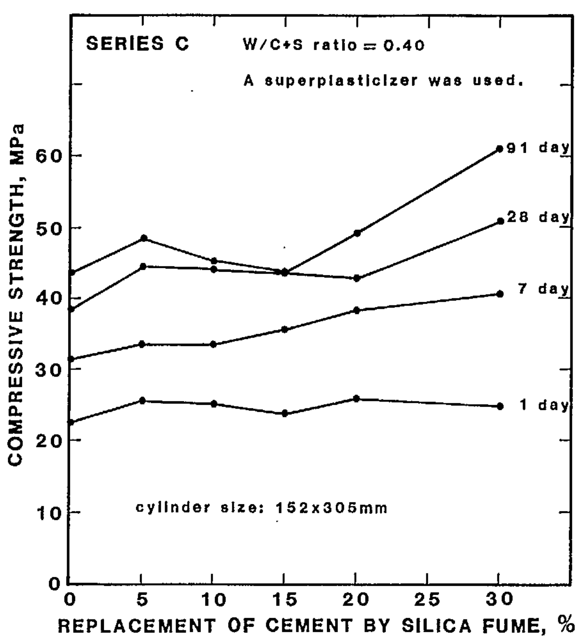

Fig. 7 - Effect of replacement of cement by silica fume on compressive strength - Series C

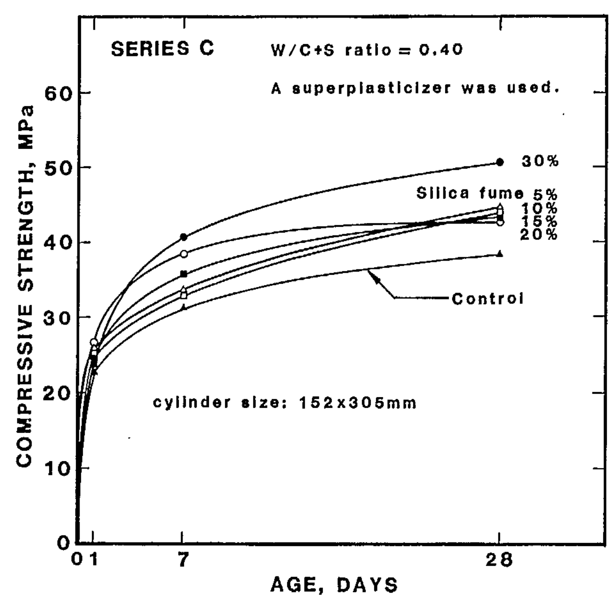

Fig. 8 - Age versus compressive strength - Series C

At 7 days and beyond, the difference in strength of concretes with and without silica fume was more marked for those incorporating 30% silica fume than for those incorporating 5 to 20%. For example, the 28-day strength of test cylinders incorporating 30% silica fume was in the order of 50 MPa compared with about 38 MPa for the control cylinders; the corresponding strengths for concretes incorporating 5 to 20% silica fume ranged from 43 to 45 MPa. The compressive strength test results for concretes incorporating 5 to 20% silica fume did not show consistent trends, especially at later ages. This is unexplained.

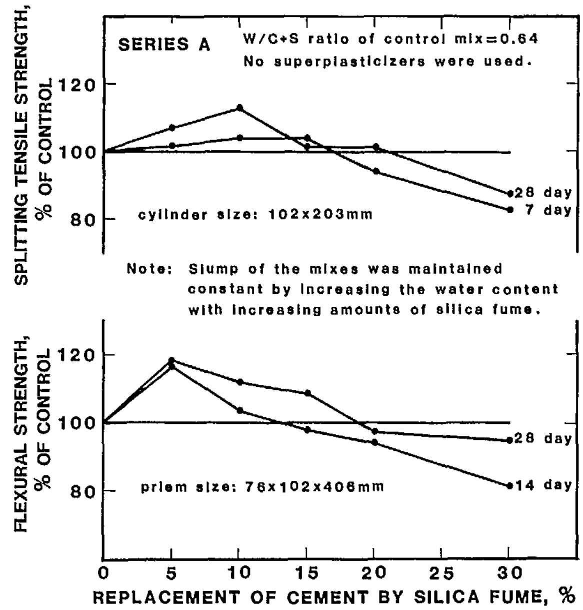

Fig. 9 - Effect of replacement of cement by silica fume on splitting-tensile and flexural strengths - Series A

FLEXURAL AND SPLITTING-TENSILE STRENGTHS

These tests were performed on specimens cast from concrete in Series A only (Table 5). The strength development pattern is somewhat similar to that for compressive strength. For concretes incorporating 5 to 15% silica fume, the 28-day splitting-tensile and flexural strengths were higher than the corresponding strengths of the control specimens (Fig. 9). The highest splitting-tensile strength of 3.6 MPa (112% of control) was obtained for concrete incorporating 10% silica fume whereas the highest flexural strength of 5.4 MPa (117% of control) was obtained for concrete incorporating only 5% silica fume.

DURABILITY OF CONCRETE PRISMS EXPOSED TO REPEATED CYCLES OF FREEZING AND THAWING (SERIES B)

Durability of concrete prisms exposed to repeated cycles of freezing and thawing (ASTM C666 Procedure A) was determined from weight, length, resonant frequency and pulse velocity of test specimens before and after cycling, and by calculating relative dynamic moduli. After cycling, the reference and test prisms were broken in flexure.

Data indicate that test prisms cast from control concrete and concrete incorporating 5, 10 and 15% silica fume performed satisfactorily in freezing and thawing tests; relative dynamic moduli were greater than 94% after 300 cycles (Fig. 10). Test prisms cast from concrete incorporating 20 and 30% silica fume started showing some damage and considerable expansion after 250 cycles (Fig. 11); at 300 cycles, their relative dynamic moduli were 83 and 68%, respectively.

The air content of fresh concrete incorporating 5 to 15% silica fume ranged from 3.8 to 4.5%; the corresponding values for concrete incorporating 20 and 30% silica fume were 4.6 and 4.2%. Published data indicate that concrete having both W:C ratio of 0.40 and an entrained air content of 4 to 5% or more performs satisfactorily when subjected to repeated freeze-thaw cycles (ASTM C666 - Procedure A). Thus, the poor performance of some of the test prisms cannot be explained in terms of lack of entrained air in fresh concrete. The air-void characteristics of the hardened concrete were determined in accordance with ASTM C457 (Modified Point-Count Method) and are given in Table 9. The air contents of the hardened concrete are shown to be in close agreement with those of the fresh concrete, however, there appears to be little relationship between these

Table 8 - Summary of freezing and thawing test results - Series B

Series	Mix No.	Type	W:C+S ratio*	Summary of freeze-thaw test results: at zero cycles: Weight, kg	Length, mm**	Longitudinal resonant frequency, Hz	Pulse velocity, m/sec	at termination of cycling: No. of cycles	Weight, kg	Length, mm	Longitudinal resonant frequency Hz	Pulse velocity, m/sec	Length change, %***	Relative dynamic modulus, %***	Residual flexural strength, %***
B	7	control	0.40	7.402	3.706	5175	4660	600	7.289	3.805	5200	4780	0.028	101	74
	8	5% silica fume + SP	0.40	7.335	3.269	5200	4670	500	7.286	3.332	5200	4730	0.018	100	75
	9	10% silica fume + SP	0.40	7.350	3.678	5250	4720	500	7.329	3.891	4900	4610	0.059	87	66
	10	15% silica fume + SP	0.40	7.327	3.510	5125	4540	525	7.289	3.752	5000	4530	0.068	95	78
	11	20% silica fume + SP	0.40	7.285	3.114	5150	4590	425	7.251	3.853	4050	3810	0.206	62	49
	12	30% silica fume + SP	0.40	7.224	3.376	5150	4660	300	7.205	3.983	4250	3820	0.170	68	32

*Water:(cement + silica fume) ratio (by weight)

**Gauge length = 358 mm

***At the end of respective cycling; residual strength was determined in relation to reference moist-cured specimens of same age

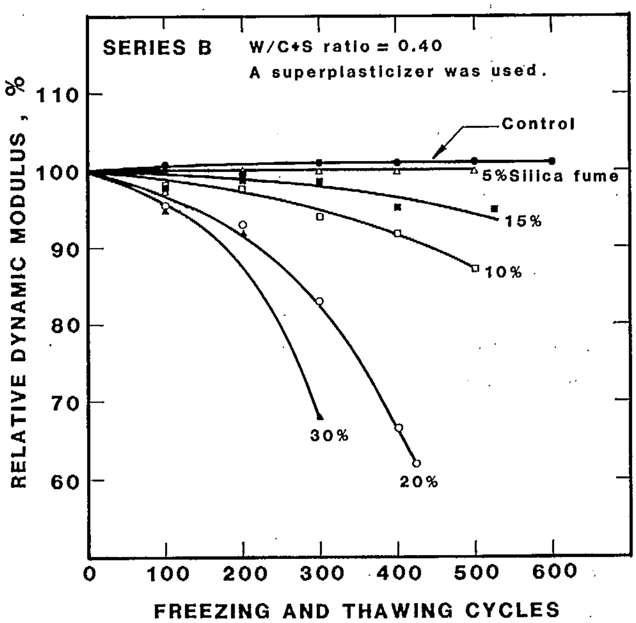

Fig. 10 - Relative dynamic modulus versus number of cycles of freezing and thawing - Series B

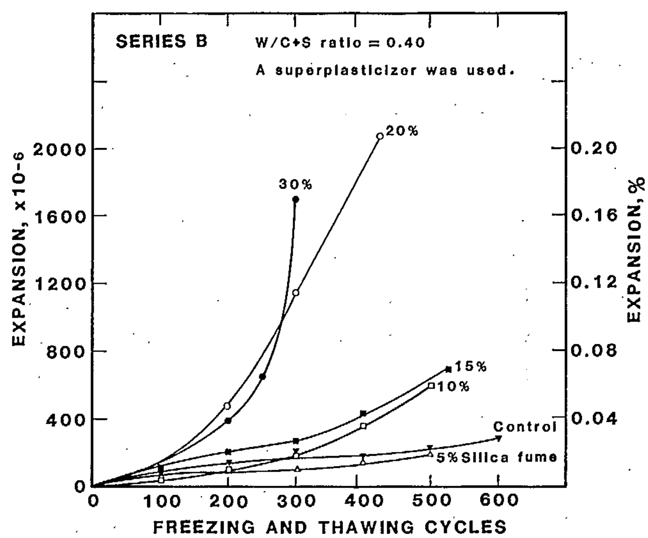

Fig. 11 - Length change versus number of cycles of freezing and thawing - Series B

air contents and the other parameters of the air-void system. For example, the control and 5% silica fume concretes showed much lower spacing factors ($\bar{L}$) and higher specific surfaces than those containing from 10 to 30% silica fume although all concretes had about the same air contents. The poor performance of concrete prisms incorporating 20 and 30% silica fume cannot be explained in terms of the high values of $\bar{L}$ alone because concrete prisms containing only 10 and 15% silica fume also had high $\bar{L}$ values. The poor durability of the former concretes may be due to the higher silica fume content resulting in a very dense cement matrix system which, in turn, adversely affects the movement of water. Another contributing factor may be the very high dosages of superplasticizer.

SHRINKAGE STRAINS AND MOISTURE LOSS

Series A - Constant Slump

Shrinkage strains and moisture loss were observed up to a maximum of only 84 days following an initial moist curing period of 28 days. The moisture loss with age was higher for the control

Table 9 - Air-void characteristics - Series B

Series	No.	Type	Air content, %*	Air:paste ratio	Specific surface, mm^{-1}	Spacing factor ($\bar{L}$), μm
B	7	control	4.5 (5.1)	0.176	22.3	221
	8	5% silica fume + SP	4.4 (4.4)	0.166	29.4	172
	9	10% silica fume + SP	3.6 (3.8)	0.135	16.3	340
	10	15% silica fume + SP	4.3 (4.5)	0.163	19.0	268
	11	20% silica fume + SP	4.6 (4.6)	0.178	17.1	285
	12	30% silica fume + SP	4.4 (4.2)	0.172	17.3	288

*Bracketed values refer to air content of fresh concrete

Table 10 - Shrinkage test results - Series A and B

				Shrinkage measurements			
Series	Mix No.	Type	W:C+S ratio*	Initial curing in water, days	Duration of drying, days	Drying shrinkage, x 10^6	Moisture loss, %
A	1	control	0.64	28	84	418	50.9
	2	5% silica fume	0.65	28	84	411	42.1
	3	10% silica fume	0.69	28	84	411	40.4
	4	15% silica fume	0.73	28	84	383	34.5
	5	20% silica fume	0.77	28	84	411	36.8
	6	30% silica fume	0.84	28	84	440	35.7
B	7	control	0.40	28	84	330	21.6
	8	5% silica fume + SP	0.40	28	84	287	16.4
	9	10% silica fume + SP	0.40	28	84	291	11.5
	10	15% silica fume + SP	0.40	28	84	316	12.9
	11	20% silica fume + SP	0.40	28	84	330	11.5
	12	30% silica fume + SP	0.40	28	84	323	10.4

*Water:(cement + silica fume) ratio (by weight)

concrete compared with concrete incorporating various percentages of silica fume even though the latter had a higher water demand during mixing (Fig. 12). The shrinkage strain of 418 x 10^{-6} for the control concrete was also slightly higher than for those incorporating silica fume; the only exception was concrete containing 30% silica fume, for which the 84-day strain value was 440 x 10^{-6} (Fig. 13).

The relatively low moisture loss and drying shrinkage of concrete incorporating silica fume was probably due to the fact that most of the additional water needed was chemically bound and thus not present in the gel or capillary pores.

Series B - Constant W:C+S Ratio

The shrinkage strains and moisture loss for Series B follow a pattern similar to those for Series A except that both moisture loss and shrinkage in absolute terms are lower for Series B (Fig. 12 to 14). For example, the moisture loss and shrinkage for concrete containing 15% silica fume in Series B are 12.9% and 316×10^{-6}; the corresponding values for Series A are 34.5% and 383×10^{-6}.

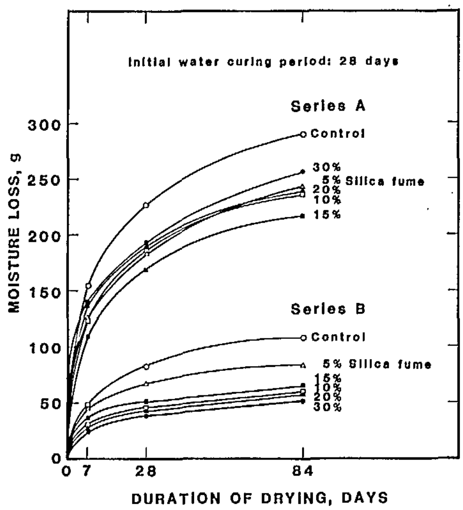

Fig. 12 - Moisture loss versus duration of drying - Series A and B

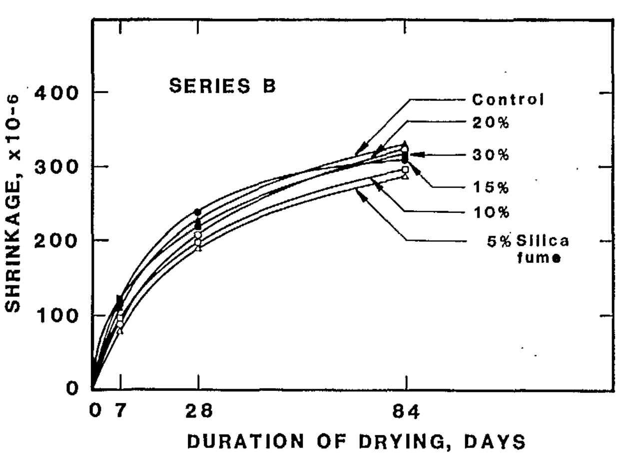

Fig. 13 - Drying shrinkage strains versus age - Series A

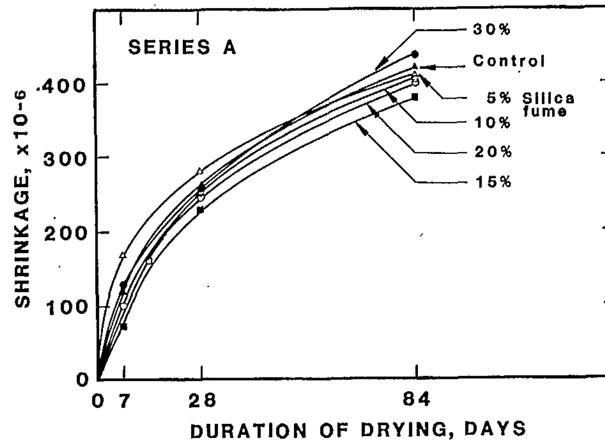

Fig. 14 - Drying shrinkage strains versus age - Series B

CONCLUSIONS

It is shown that silica fume, when used in concrete as a partial replacement for cement, performs as a highly efficient pozzolanic material. Specifically, for non-superplasticized concrete mixes, the water demand increases with increasing silica fume content; notwithstanding the increased water demand thus higher W:C+S ratios, an increase occurs in compressive strength at later ages. This is particularly so for concrete incorporating lower percentages of silica fume.

For superplasticized concrete maintained at a W:C+S of 0.40 some increase is indicated in compressive strength at all ages regardless of the percentage of silica fume used. However, as far as strength gain is concerned, the use of silica fume in low water-to-cement mixes appears to be less efficient than in mixes of high water-to-cement ratios.

Concrete prisms incorporating 0 to 15% silica fume at a W:C+S of 0.40 perform satisfactorily when subjected to 300 cycles of freezing and thawing (ASTM C666 - Procedure A) regardless of the $\bar{L}$ values. However, concrete prisms incorporating 20 to 30% of silica fume show excessive expansion and relatively low dynamic moduli after

300 cycles of freezing and thawing. Their poor performance cannot be explained in terms of high $\bar{L}$ values alone; probably it is due to the higher silica fume content and higher dosages of superplasticizer.

The drying shrinkage of concrete incorporating silica fume is generally comparable to that of control concrete regardless of the W:C+S ratio.

RECOMMENDATIONS

It is recommended that further studies be made to determine the mechanical properties of concrete having high water-to-cementitious materials ratios. The resulting loss in slump due to incorporating silica fume should be compensated for by adding a superplasticizer. Exploratory work following the above investigation has indicated that this approach may be the most efficient when using silica fume in concrete.

REFERENCES

1. Malhotra, V.M., Berry, E.E. and Wheat, T.A. (editors); Proceedings, Seminar on Energy and Resource Conservation in the Cement and Concrete Industry; CANMET, Energy, Mines and Resources Canada; 1976.

2. Berry, E.E. "Fly ash for use in concrete. Part 1 - A critical review of the chemical, physical and pozzolanic properties of fly ash"; CANMET Report 76-25; CANMET, Energy, Mines and Resources Canada; 1976.

3. Berry, E.E. and Malhotra, V.M. "Fly ash for use in concrete. Part II - A critical review of the effects of fly ash on the properties of concrete"; CANMET Report 78-16; CANMET, Energy, Mines and Resources Canada; 1978.

4. Malhotra, V.M. "Strength and freeze-thaw characteristics of concrete incorporating granulated blast-furnace slag"; CANMET Report 79-38; Energy, Mines and Resources Canada; 1979.

5. Malhotra, V.M., Carette, G.G. and Bremner, T.W. "Durability of concrete containing granulated blast-furnace slag or fly ash or both in marine environment"; CANMET Report 80-18E; CANMET, Energy, Mines and Resources Canada; 1980.

6. Mukherjee, P.K., Loughborough, M.T. and Malhotra, V.M. "Developments of high-strength concrete incorporating a large percentage of fly ash and superplasticizers"; Division Report MRP/MSL 81-124(OP&J); CANMET, Energy, Mines and Resources Canada; 1981.

7. Traetteberg, A. "Waste materials in the construction industry"; unnumbered paper from Cement and Concrete Research Institute, Norweigan Institute of Technology; Trondhiuim, Norway; 1977.

8. Bache, H.H. "Densified cement/ultra-fine particle-based materials"; paper presented 2nd CANMET/ACI International Conference on Superplasticizers in Concrete; Ottawa, Canada; 1981.

9. Aitcin, P.C. and Pinsonneault, P. "Utilisation de la poussière de silice submicroscopique des usines de silicium et de ferrosilicium dans les bétons"; Proc Symposium on Progress in Concrete; Quebec City, Quebec, Canada; 1981; 185-213; (Available from Department of Civil Engineering, University of Sherbrooke, Sherbrooke, P.Q.).

10. Buck, A. and Burkes, J.P. "Characterization and reactivity of silica fume"; Proc Third International Conference on Cement Microscopy; Houston, U.S.A.; 279-285; 1980.

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