Strength and Freezing-and-Thawing Resistance of Concrete Incorporating Condensed Silica Fume

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Synopsis: This report gives results of laboratory investigations to determine the strength characteristics and the pore size distributions of mortar and concrete incorporating condensed silica fume from a Japanese sourse. This report also gives results of the shrinkage, permeability and freezing and thawing resistance of concrete incorporating silica fume.

A series of mortar mixes was made with a water-to-cement plus silica fume ratio of 0.65, and the percentage of silica fume used as partial replacements for normal portland cement of 0, 5, 10, 20 and 30 % by weight.

A total of twenty three concrete mixes were made with the water-to-cement plus silica fume ratio(W/C+S) ranging from 0.25 to 0.55, and the percentage of silica fume used as partial replacement for cement of 0, 5, 10, 20 and 30 % by weight. All mixes were not air-entrained except mix with the W/C+S of 0.55 which was air-entrained. A superplasticizer was used for all the mixes incorporating condensed silica fume.

Condensed silica fume improved the compressive strength of the mortar and the concrete at 28 and 91 days and the impermeability of the concrete. The drying shrinkage of the condensed silica fume concrete was comparable to that of the control concrete without silica fume.

Non air-entrained silica fume concretes with the W/C+S of 0.35, 0.45, and 0.55 showed low durability factors, although the air-entrained concrete with a W/C+S of 0.25 performed satisfactorily to the repeated cycles of freezing and thawing. The air-entrained concrete incorporating 20 and 30 % silica fume with a W/C+S of 0.55 showed very poor durability as compared with the control concrete.

Keywords: air entrainment; compressive strength; concretes; drying shrinkage; flexural strength; freeze-thaw durability; mortars (material); permeability; porosity; pozzolans; silica.

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INTRODUCTION

Silica fume is a by-product of the ferro-silicon and silicon metal industry. Investigations on the performance of silica fume in concrete have been going on in north European countries for about 10 years. Lately some attention has been given to the use of condensed silica fume as a partial replacement for cement. Little work has been done in Japan on the durability of non air-entrained and air-entrained concrete containing silica fume, although some papers(1-4) on the use of silica fume have been presented. This report, therefore, gives results of a study dealing with the strength and freezing and thawing resistance of concrete incorporating condensed silica fume.

EXPERIMENTAL

Materials

Normal portland cement was used in the mixes. The chemical and physical properties of the cement are shown in Table 1.

Condensed silica fume from a Japanese silicon alloy manufacturing plant was used. Its chemical and physical properties are given in Table 2.

The fine aggregate for cement mortar was graded standard sand. The fine aggregate for concrete was marine sand and the coarse fraction consisted of 20-mm crushed amphibole. The physical properties of both the fine and coarse aggregates are given in Table 3.

A resinous salt type air-entraining agent, a lignousulfonic acid type water-reducing agent and a sulfonated naphthalene fomaldehyde condensate superplasticizer of Japanese origin were used as admixtures for concrete.

Mix Proportions

The graded fine aggregate was weighed in room dry condition. The proportions of materials for the cement mortar were one part of cement to 2 parts of graded standard sand by weight. A water-to-cement plus silica fume ratio(W/C+S) of 0.65 was used for all portland cement mortars. For mixes incorporating condensed silica fume, any loss in flow was compensated for by the use of a superplasticizer to ensure a flow of 230±10 as measured by JIS R 5201. The control mix without fume had a flow of 233.

The mortar mix proportioning details for Series A are shown in Table 4. Series A consisted of non air-entrained mortar mixes incorporating the condensed silica fume at 0, 5, 10, 20, 30 % replacement levels.

Series B consisted of twenty non air-entrained concrete mixes with the W/C+S of 0.25, 0.35, 0.45, 0.55 and three air-entrained concrete mix with a W/C+S of 0.55. For each W/C+S ratio, five mixes each were made: these included a control mix without condensed silica fume and four mixes incorporating the silica fume at 5, 10, 20, 30 % replacement levels. For the air-entrained concrete with a W/C+S of 0.55, two mixes incorporating the fume at 20 and 30 % replacement levels were made.

The mix proportioning details for Series B are shown in Table 5. The control mixes were proportioned to have a slump 100±20 mm. For all mixes with a W/C+S of 0.25, a superplasticizer was used. For mixes incorporating condensed silica fume, any loss in slump was compensated for by using a superplasticizer.

Flow of Mortar and Properties of Fresh Concrete

The flows of mortar and the properties of fresh concrete, that is, temperature, slump, air content are given in Table 4 and Table 5, respectively.

PREPARATION AND CASTING OF TEST SPECIMENS

Three 4x4x16-cm prisms were cast from each mortar mix in Series A for the flexural strength and the compressive strength. After casting, the molded specimens were left in the casting room at about 20 °C until required for testing.

The number of specimens cast from each concrete mix in Series B is shown in Table 6. Thirty six 10x20-cm cylinders for compression testing, three 15x30-cm cylinders for permeability testing and one 10x10x40-cm prisms for shrinkage were cast for each non-air-entrained concrete mix. Also three 10x10x40-cm prisms for freezing and thawing studies were cast from each mix of Series B.

After casting, the twenty seven cylinders for compression testing were stored in chambers at 10, 20 and 30 °C for 24 hours. They were then demoulded and cured at each temperature until the test age. The remaining nine cylinders were stored at 30 °C for one hour after casting, cured in 65 °C water vapor at atmospheric pressure for three hours and stored in 20 °C water until the test age.

Three hollow cylindrical specimens, 150 mm outside diameter, 20 mm inner diameter, and 300 mm high, for the permeability test and one 10x10x40-cm prism for shrinkage studies were cast for the W/C+S of 0.25 and 0.55. These included one control mix and two mixes incorporating the fume content of 20 and 30 %.

Three 10x10x40-cm prisms for freezing and thawing studies were cast for each mix given in Table 5. The specimens for permeability, shrinkage and freeze-thaw studies were cured in 20 °C water until the test age after demoulding.

TESTING OF SPECIMENS

Three 4x4x16-cm prism for each mix of Series A were used for the flexural strength at each 7, 28 and 91 days. The compressive strength was determined by using the portions of prisms broken in flexure in accordance with JIS R 5201. All concrete specimens for compression testing were capped and tested in accordance with JIS A 1108.

Pore size distributions of mortar and concrete were determined by mercury penetration technique.

The specimens for shrinkage testing were cured in water at 20 °C for 28 days. They were then stored in a room at 20 °C and relative humidity 60 percent. The shrinkage tests were initiated at 28 days. Strains in the shrinkage test were measured to the nearest ten-millionth by a contact gage.

The specimens for permeability testing were cured in water at 20 °C until 91 days. They were then dried at 20 °C for 7 days. The water pressure of 0.98 MPa was applied to the inner surface for 48 hours. The mean depth of radial penetration of water was measured after breaking the specimen in accordance with JIS A 1113. The diffusion coefficient of water computed from the formula

$$\beta_i^{\,2} = \alpha \frac{D_m^{\,2}}{4\,t\,\xi^2} \quad (5) \qquad\text{———————}\qquad (1)$$

where $\beta_i^{\,2}$ =diffusion coefficient; D_m=mean depth of penetration of water; t=the duration of test; α=factor on the duration of test; ξ= factor on the magnitude of the water pressure, respectively.

At 28 days, two prisms from each concrete mix of Series B were removed from 20 °C water and cooled to 5 °C in a freezing and thawing cabinet. The all measurements of the specimens subjected to repeated freezing-thawing cycles were done at this temperature.

After initial measurements, two prisms were subjected to freezing and thawing cycles according to ASTM C 666, procedure A.

One 10x10x40-cm prism for each mix was used for air-void parameter determinations of the hardened concrete. The measurement of the air-void system was made in accordance with ASTM C 457 by using a stereoscopic microscope.

TEST RESULTS

The strength results of Series A: mortar are shown in Fig.1 and 2. Pore size distribution curves of mortar at 7, 28 and 91 days are shown in Fig.3. A summary of compressive strength test results for Series B is given in Table 7. Plots of compressive strength test results are shown in Fig.4 and 5. The pore size distribution curves of concrete with a W/C+S of 0.35 and 0.55 are shown in Fig.6. The total pore volume of each concrete is shown in Table 7. The drying shrinkage data are given in Table 9. The permeability test results are given in Table 10.

DISCUSSION OF RESULTS

Strength Characteristics and Pore Size Distributions of Cement Mortars

The flexural and compressive strength data are plotted in Fig.1 and Fig.2. Compared to the control mortar, that with condensed silica fume shows loss in the compressive strength at curing periods as early as seven days. There is a small decrease in strength with increasing amounts of the fume at 7 days. At 28 days, however, the mortars incorporating 10, 20 and 30 % condensed silica fume show greater flexural and compressive strengths compared to the control mortar. At 91 days, the mortar with the fume shows greater flexural and compressive strengths compared with the control mortar. At 91 days, there is an increase in the compressive strength of mortar with the increasing amounts of the fume used. For example, the compressive strengths are 42.3, 43.0, 44.3, 56.7 and 58.6 MPa for 0, 5, 10, 20 and 30 % silica fume, respectively.

The pore size distribution curves for mortars are shown in Fig.3. The content of mercury intruded into the specimens decreased with curing period over the full range of pressure. Cheng-yi and Feldman(6) showed that the pore size distribution curves for all samples at high pressure are concave to the pressure axis. In this investigation, the curves for all specimens at high pressures are also concave to the axis of abscissa. From Fig.3(a), it is evident that at 7 days, the volume of large pores above about 400 μm is somewhat higher for the mortar incorporating the fume than for the control mortar.

At 91 days, there is a decrease in the total volume of pores larger than about 400 μm with the increasing amount of the condensed silica fume used. Correspondingly, there is an increase in the flexural and compressive strengths of mortar with increasing amount of the fume at 91 days.

Strength Characteristics and Pore Size Distributions of Concrete

A summary of the compressive strengths of concrete are given in Table 7. The incorporation of condensed silica fume does not result in significant changes at 7 days in the compressive strength of concrete at curing temperature of 10 °C. At curing temperature of 20, 30 and 65 °C(steam curing), there is an increase in the strength at 7 days with the using of the fume. For example, the compressive strength of concrete with the W/C+S of 0.25 is 50.2, 75.2 and 72.8 MPa for the control, 20 and 30 % silica fume concrete, respectively. At 28 and 91 days, there is an increase in the strength with the using of the fume for concrete with a W/C+S of 0.55 and at a curing temperature of 10 °C. This is true for both air-entrained and non air-entrained concretes.

The effect of curing temperatures on the compressive strengths are shown in Fig.5. There is an increase in the strength for a W/C+S of 0.55 and 0.25 with increasing curing temperatures. At 91 days, however, for concrete with a W/C+S of 0.25 and incorporating 20 % condensed silica fume and for that with a W/C+S of 0.55 and incorporating 20 and 30 % fume, the compressive strength for curing temperature of 30 °C is less as compared with that for 20 °C.

The pore size distribution results of concrete with a W/C+S of 0.25 to 0.55 were determined by mercury penetration technique. The total pore volume results are given in Table 8. The content of mercury intruded into the concrete specimen increased with the increasing of W/C+S, although there are some exceptions. For example, the total pore volume of concrete with 30 % silica fume are 0.0271, 0.0310, 0.0400 and 0.0612 cc/g for the W/C+S of 0.25, 0.35, 0.45 and 0.55, respectively.

The pore size distribution data of the concrete with the W/C+S of 0.35 at 28 days is shown in Fig.6. It has shown that there is a decrease in the coarser porosity in the concrete incorporating silica fume as compared with control concrete without silica fume, although the total pore volume remains nearly the same. This fact was also showed by Mehta and Gjørv (7).

Drying Shrinkage of Concrete Prisms

The drying shrinkage of silica fume concrete with a W/C+S of 0.25 and 0.55 is shown in Table 9.

The amount of mixing water is 125 and about 180 kg/m^3 for W/C+S of 0.25 and 0.55, respectively. The concrete with W/C+S of 0.55 showed high drying shrinkage as compared with the concrete with the W/C+S of 0.25. This may be due to the decrease in the mixing water for the concrete with the W/C+S of 0.25.

There is no apparent difference in the drying shrinkage of the control, 20 % and 30 % silica fume concrete for W/C+S of 0.25 and 0.55.

Permeability of Concrete Specimens

Table 10 gives the water diffusion coefficient of silica fume concrete with the W/C+S of 0.25 and 0.55.

With 20 % condensed silica fume, the diffusion coefficient of the concrete with a W/C+S of 0.25 was reduced from 8.37×10^{-4} to 7.19×10^{-4} cm^2/sec. The diffusion coefficient of the non air-entrained concrete with the W/C+S of 0.55 was reduced from 18.95×10^{-4} to 10.49×10^{-4} cm^2/sec with the using of 20 % silica fume. This reduction in diffusion coefficient may be due to the decrease in the coarser porosity of the concrete incorporating silica fume, although the total pore volume remains nearly the same.

Air-void Parameters of Hardened Concrete

The air-void parameters of hardened concrete were determined by the ASTM Standard Practice for Microscopic Determination of Air-void Content and Parameters of the Air-void System in Hardened Concrete(C457). Table 11 gives the air-void parameters.

The void spacing factor $\bar{L}$ for non air-entrained concrete was greater than 0.350 mm. That for air-entrained concrete with the W/C+S of 0.55 was 0.250, 0.384 and 0.352 mm for 0, 20 and 30 % silica fume, respectively.

For control concrete, there is a decrease in the spacing factor with the increasing value of W/C+S. For example, the spacing factor is 0.794, 0.550, 0.385 and 0.368 mm for the W/C+S of 0.25, 0.35, 0.45 and 0.55, respectively.

The concrete incorporating silica fume shows an increase in the spacing factor with the increasing amount of condensed silica fume. For example, for the concrete with the W/C+S of 0.35, the void spacing factor is 0.550, 0.613, 0.672 and 0.689 mm for 0, 5, 10, 20 and 30 % fume, respectively. However, there are some exceptions in other concretes incorporating silica fume, although the difference in the spacing factor among them is small.

Freezing and Thawing Resistance of Concrete

Freezing and thawing resistance of concrete prisms was investigated by determining weight and resonant frequency before and after the freezing and thawing cycles.

For air-entrained concrete with a W/C+S of 0.55, only control concrete showed good freezing and thawing resistance and the durability factor was 78 % after 300 cycles. The air-entrained concrete prisms with a W/C+S of 0.55 and incorporating 20 and 30 % silica fume performed poorly as compared with the control concrete. This poor durability seeems to be attributed directly to the high spacing factor value, inspite of 4.9 % entrained air in fresh concrete incorporating 30 % silica fume, and the very dense cement matrix system with high strength which prevents the movement of water to the unfrozen area (7).

For non air-entrained concrete with a W/C+S of 0.25, regardless of the amount of silica fume used, the concrete prisms showed a very good freezing and thawing resistance and the durability factor was very high even after 500 freezing and thawing cycles. The reason why the non air-entrained concrete showed an excellent freezing and thawing resistance, although the void spacing factor of that is high, may be due to the very dense matrix which has the high tensile strength enough to overcome the hydraulic pressure due to the formation of ice.

For non air-entrained concrete with a W/C+S of 0.35, the durability factors of concrete incorporating 10, 20 and 30 % fume were less than 60 %, although that of the control concrete were 82 %. The condition of the concrete prisms with a W/C+S of 0.35 and incorporating 5 % silica fume was somewhat better and the durability factor was 64 %. There is an increase in the void spacing factor with an increasing amount of silica fume for non air-entrained concrete with a W/C+S of 0.35 as well as for the air-entrained concrete. This may explain why the concrete incorporating silica fume shows less freezing and thawing resistance as compared with the control concrete. There is the similar trend in the non air-entrained concrete with a W/C+S of 0.45 and 0.55.

CONCLUSIONS

1. The mortar cubes incorporating condensed silica fume showed loss in the compressive strength at curing periods of 7 days as compared with the control mortar without fume. At 28 and 91 days, however, the mortar cubes with silica fume showed greater flexural and compressive strengths as compared with the control mortar specimens.
2. The incorporation of condensed silica fume in concrete results in significant increases in the compressive strength at 28 and 91 days.
3. By the use of the mercury porosimetry measurements, it has been shown that the number of voids below 400 μm increased in the mortar and the concrete incorporating silica fume.
4. The drying shrinkage of concrete containing silica fume was comparable to that of the control concrete without silica fume for a W/C+S of 0.25 and 0.55. For 340 and 500 kg/m^3 cement contents, the concrete incorporating silica fume was more dense and had increased impermeability than the control concrete.
5. For non air-entrained concrete with a W/C+S of 0.25 and regardless of the amount of silica fume, the concrete prisms showed very

high freezing and thawing resistance. The use of non air-entrained silica fume concrete with W/C+S of 0.35, 0.45 and 0.55, however, is not recommended when it is to be subjected to repeated cycles of freezing and thawing.

6. The air-entrained concrete incorporating 20 and 30 % silica fume at a W/C+S of 0.55 showed very poor freezing and thawing resistance, although the air-entrained control concrete without silica fume performed satisfactorily in the freezing and thawing test performed in accordance with ASTM C 666.

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Table 1 : Chemical and Physical Properties of Cement

Chemical Properties (%)									
L.OI.	Insol.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Total	
0.6	0.1	22.3	5.7	3.0	63.3	1.8	3.1	98.9	
Physical Properties									
Specific Gravity	Specific Surface Area (cm^2/g)	Strength at 3 to 28 day (MPa)							
		Bending			Compressive				
		3 day	7 day	28 day	3 day	7 day	28 day		
3.15	3260	3.33	4.90	6.96	14.5	24.3	41.8		

Table 2 : Chemical and Physical Properties of Condensed Silica Fume for Use in Concrete

Chemical Properties								
Chemical Composition (%)							PH	
L.OI.	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Total C		
2.0∿3.0	88.0∿91.0	0.2	0.1	0.1	1.0	0.5	8.1∿8.6	
Physical Properties								
Specific Gravity	Particle Shape	Moisture Content (%)	Particle Size Distribution (%)					
			10µm>	1∿10µm	0.5∿1µm	0.1∿ 0.5µm	0.1µm<	
2.24	Sphere	0.2∿0.6	4.7	4.9	15.5	53.7	21.2	

Table 3 : Physical Properties of Aggregates for Concrete

Aggregate		Grading	Fineness Modulus	Specific Gravity	Water Absorptipn (%)
Fine Aggregate	Graded Standard Sand*	105 297 um	0.97	2.63	-
	Marine Sand	5.0 mm	2.65	2.59	1.5
Coarse Aggregate	Crushed Amphible	5 20 mm	6.93	2.89	1.1

* The sand used for making mortar test specimens is natural silica sand Toyoura, Yamaguchi in Japan.

Table 4 : Mix proportions and flows of Mortar Specimens in Series A

Mix Notations	S/C+S* (%)	Silica Fume (g)	Cement (g)	Water (g)	Sand (g)	Super-plasti-cizer (g)	Flow By JIS method (mm)
M0	0	0	600	390	1200	0	233
M5	5	30	570	390	1200	2.85	235
M10	10	60	540	390	1200	4.86	235
M20	20	120	480	390	1200	9.12	230
M30	30	180	420	390	1200	12.60	232

* By Weight

Table 5 : Mix Proportions and Properties of Fresh Concrete in Series B

Type of concrete	Mix No.	Mix Proportions						Properties of Fresh Concrete		
		W/(C+S) (By Weight)	Sand-coarse aggregate ratio,% (By Volume)	Cement, kg/m^3	Silica Fume, %*	Silica Fume, kg/m^3	Dosage of Superplasticizer, kg/m^3	Temperature, °C	Slump, mm	Air Content, %
Non air-entrained concrete	1	0.25	0.61	500	0	0	20.00	28	90	2.0
	2	0.25	0.61	475	5	25	17.50	18	75	2.1
	3	0.25	0.61	450	10	50	15.00	18	100	1.7
	4	0.25	0.61	400	20	100	9.00	29	90	2.0
	5	0.25	0.61	350	30	150	14.00	28	100	1.7
	6	0.35	0.64	450	0	0	3.60	21	80	2.1
	7	0.35	0.64	427.5	5	22.5	4.50	21	75	1.8
	8	0.35	0.64	405	10	45	4.95	21	95	1.6
	9	0.35	0.64	360	20	90	4.50	21	90	1.6
	10	0.35	0.64	315	30	135	7.88	20	80	1.6
	11	0.45	0.72	390	0	0	1.56	20	105	2.2
	12	0.45	0.72	370.5	5	19.5	3.12	20	80	1.7
	13	0.45	0.72	351	10	39	2.73	21	90	1.9
	14	0.45	0.72	312	20	78	3.51	22	110	1.7
	15	0.45	0.72	273	30	117	6.24	21	105	1.9
	16	0.55	0.82	330	0	0	-	27	110	1.5
	17	0.55	0.82	323	5	17	0.68	21	105	2.2
	18	0.55	0.82	306	10	34	1.36	21	105	2.2
	19	0.55	0.82	272	20	68	3.23	28	85	1.8
	20	0.55	0.82	238	30	102	5.44	28	85	1.8
Air entrained concrete	21	0.55	0.82	330	0	0	0.83	29	120	4.2
	22	0.55	0.82	264	20	66	3.33	28	125	4.3
	23	0.55	0.82	231	30	99	4.29	29	115	4.9

*Percentage replacement of cement by weight

Table 6 : The Number of Specimens in Series B

Type of Concrete	Mix No.	Compression Test Cylinders ϕ 10x20-cm			Permeability Test Hollow Cylinders ϕ 15x30-cm	Shrinkage Test Prisms 10x10x40-cm	Freezing and Thawing Test Prisms 10x10x40-cm
		7days	28days	91days	91days	-	-
Non air-entrained concrete	1	12	12	12	3	1	3
	2	0	3	3	0	0	3
	3	0	3	3	0	0	3
	4	12	12	12	3	1	3
	5	12	12	12	3	1	3
	6	0	3	3	0	0	3
	7	0	3	3	0	0	3
	8	0	3	3	0	0	3
	9	0	3	3	0	0	3
	10	0	3	3	0	0	3
	11	0	3	3	0	0	3
	12	0	3	3	0	0	3
	13	0	3	3	0	0	3
	14	0	3	3	0	0	3
	15	0	3	3	0	0	3
	16	12	12	12	3	1	3
	17	0	3	3	0	0	3
	18	0	3	3	0	0	3
	19	12	12	12	3	1	3
	20	12	12	12	3	1	3
Air entrained concrete	21	12	12	12	3	1	3
	22	12	12	12	3	1	3
	23	12	12	12	3	1	3

Table 7 : Summary of Compressive Strengths*
Series B : Concrete

Type of concrete	Mix No.	Compressive Strength* of 10x20-cm Cylinders at Various Curing Temperatures and Ages											
		7 days				28 days				91 days			
		10°C	20°C	30°C	Steam**	10°C	20°C	30°C	Steam**	10°C	20°C	30°C	Steam**
Non air-entrained concrete	1	44.0	45.7	50.2	46.6	51.8	54.6	57.4	54.0	58.2	63.6	70.9	66.8
	2	-	-	-	-	-	58.5	-	-	-	65.5	-	-
	3	-	-	-	-	-	68.3	-	-	-	75.0	-	-
	4	48.2	56.4	75.2	64.2	64.1	79.7	82.9	76.4	84.0	89.7	89.0	84.7
	5	44.3	51.0	72.8	71.1	68.6	75.8	89.9	87.1	84.5	87.1	93.6	90.8
	6	-	-	-	-	-	55.0	-	-	-	58.0	-	-
	7	-	-	-	-	-	62.1	-	-	-	67.9	-	-
	8	-	-	-	-	-	64.3	-	-	-	72.0	-	-
	9	-	-	-	-	-	64.0	-	-	-	72.7	-	-
	10	-	-	-	-	-	62.9	-	-	-	72.3	-	-
	11	-	-	-	-	-	41.3	-	-	-	47.6	-	-
	12	-	-	-	-	-	49.0	-	-	-	61.2	-	-
	13	-	-	-	-	-	57.3	-	-	-	66.1	-	-
	14	-	-	-	-	-	52.7	-	-	-	62.6	-	-
	15	-	-	-	-	-	50.2	-	-	-	61.6	-	-
	16	19.9	18.5	23.3	24.3	23.8	25.0	30.3	29.0	26.6	37.4	34.0	31.9
	17	-	-	-	-	-	27.9	-	-	-	45.7	-	-
	18	-	-	-	-	-	33.6	-	-	-	47.6	-	-
	19	20.6	20.6	30.6	24.1	30.7	34.3	37.7	31.9	43.6	44.5	39.5	37.6
	20	20.3	21.3	31.9	26.9	33.3	36.4	39.2	36.2	45.4	47.6	47.0	40.7
Air entrained concrete	21	17.2	12.6	22.8	20.5	22.3	23.5	23.9	23.7	29.1	30.9	29.9	25.3
	22	19.6	23.4	29.6	27.7	28.4	32.1	34.7	33.0	35.2	36.8	39.1	33.1
	23	17.5	20.9	23.3	30.9	24.8	31.0	40.0	30.9	34.3	38.1	37.5	33.9

* Each Compression test result is the average of tests on three cylinders
** Atmospheric-pressure steam curing

Table 8 : Total Pore Volume of Concrete

Type of concrete	Mix No.	W/C+S (By Weight)	Total Pore Volume (cc/g)
Non air-entrained concrete	1	0.25	0.0232
	2		0.0228
	3		0.0236
	4		0.0255
	5		0.0271
	6	0.35	0.0353
	7		0.0335
	8		0.0238
	9		0.0333
	10		0.0310
	11	0.45	0.0593
	12		0.0354
	13		0.0442
	14		0.0393
	15		0.0403
	16	0.55	0.0649
	17		0.0476
	18		0.0534
	19		0.0697
	20		0.0612
Air entrained concrete	21	0.55	0.0787
	22		0.0638
	23		0.0654

Table 9 : Drying Shrinkage Data of Concrete Prisms

Mix No.	W/C+S (By Weight)	Drying Shrinkage* of 10x10x40-cm Prisms at Various Ages, 10^{-6}			
		Duration of Drying, days			
		7	28	56	91
1	0.25	120	263	318	368
4		160	252	313	364
5		173	265	293	378
16	0.55	145	325	547	645
19		108	350	498	620
20		108	403	525	618
21	0.55	207	448	535	659
22		258	436	610	645
23		230	435	609	647

* The specimens for shrinkage testing were stored in a room at 20°C and relative humidity 60 percent.

Table 10 : Diffusion Coefficients of water in 15x30-cm Concrete Cylinders

Mix No.	W/C+S (By Weight)	Diffusion Coefficients* (15x30-cm Cylinders) at 91 days, $x10^{-4}$ cm^2/sec
1	0.25	8.37
4		7.19
5		6.34
16	0.55	18.95
19		10.49
20		10.95
21	0.55	19.86
22		13.26
23		17.80

* Each permeability test result is the mean of tests on three cylinders.

Table 11 : Air-Void Parameters of Hardened Concrete and Durability Factors Series B: concrete

Type of concrete	Mix No.	W/(C+S) (By Weight)	Replacement of Cement by Silica Fume, %	Air Content of Fresh Concrete, %	Air Void Parameters of Hardened Concrete: Voids in Concrete, %	Specific Surface, mm^{-1}	Spacing Factor, mm	Durability Factor*, %
Non air-entrained concrete	1	0.25	0	2.0	1.9	9.5	0.794	98
	2	0.25	5	2.1	2.3	9.8	0.763	95
	3	0.25	10	1.7	2.0	9.6	0.753	95
	4	0.25	20	2.0	3.3	6.4	0.879	95
	5	0.25	30	1.7	1.6	10.4	0.816	93
	6	0.35	0	2.1	2.0	11.8	0.550	82
	7	0.35	5	1.8	2.9	10.6	0.613	64
	8	0.35	10	1.6	1.8	6.6	0.661	59
	9	0.35	20	1.6	1.6	10.4	0.672	55
	10	0.35	30	1.6	1.1	8.9	0.689	46
	11	0.45	0	2.2	2.2	18.7	0.385	47
	12	0.45	5	1.7	1.4	15.7	0.553	45
	13	0.45	10	1.9	3.3	9.8	0.602	43
	14	0.45	20	1.7	2.6	10.6	0.612	20
	15	0.45	30	1.9	3.5	9.6	0.576	14
	16	0.55	0	1.5	2.1	19.9	0.368	35
	17	0.55	5	2.2	2.8	12.0	0.543	33
	18	0.55	10	2.2	2.7	12.2	0.535	24
	19	0.55	20	1.8	2.3	12.7	0.540	11
	20	0.55	30	1.8	3.0	13.7	0.473	7
Air entrained concrete	21	0.55	0	4.2	4.6	20.5	0.250	78
	22	0.55	20	4.3	5.4	12.5	0.384	33
	23	0.55	30	4.9	4.5	14.9	0.352	28

* These values have been calculated on the basis of the completion of 300 cycles of freezing and thawing.

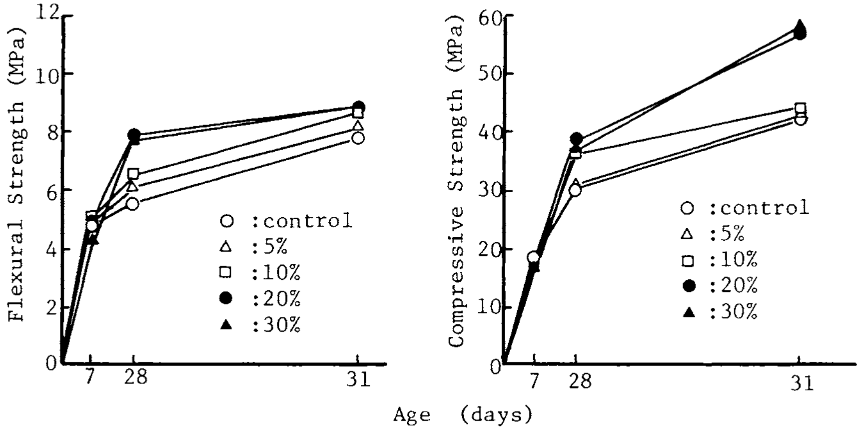

Fig. 1 Age versus strength of mortar
(a) Flexural strength
(b) Compressive strength

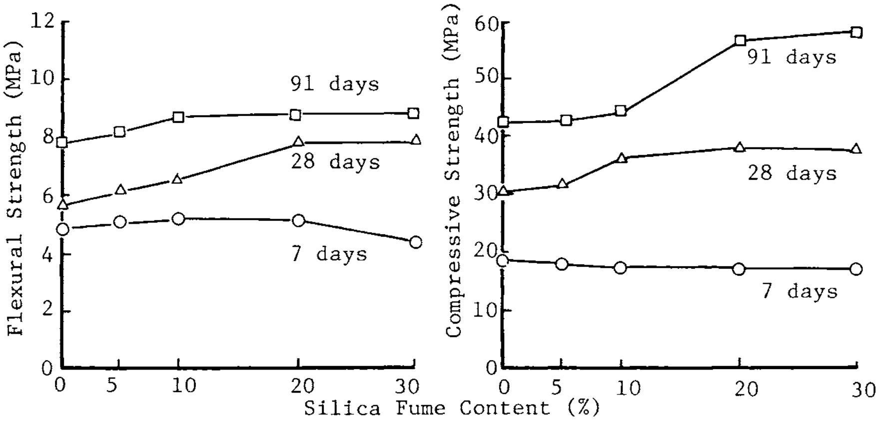

Fig. 2 Silica fume content versus strength of mortar
(a) Flexural strength
(b) Compressive strength

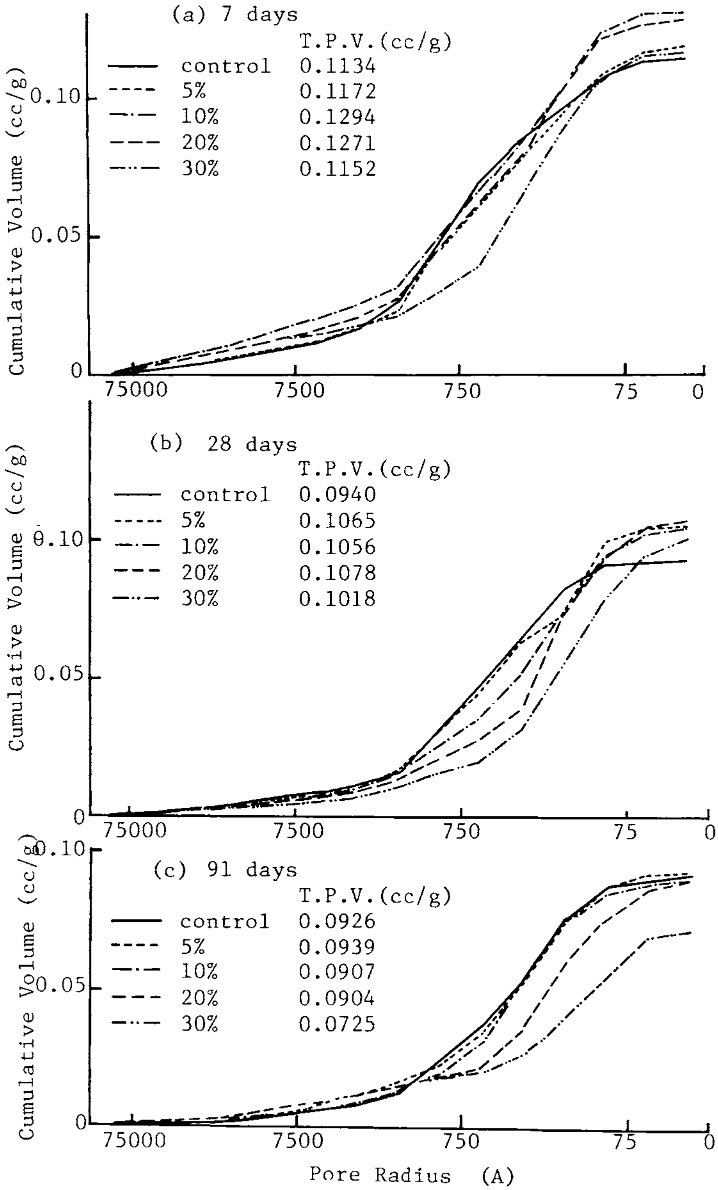

Fig.3 Pore size distribution curves of cement mortar with different silica fume content (a) 7 days (b) 28 days (c) 91 days

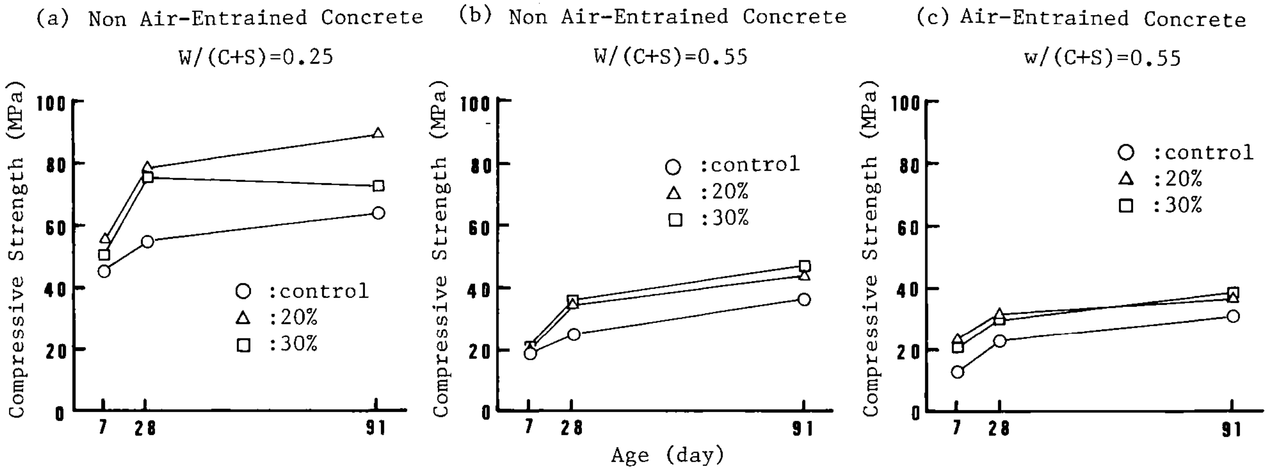

Fig. 4 Age versus compressive strength
(a) Non air-entrained concrete (W/(C+S)=0.25)
(b) Non air-entrained concrete (W/(C+S)=0.55)
(c) Air-entrained concrete (W/(C+S)=0.55)

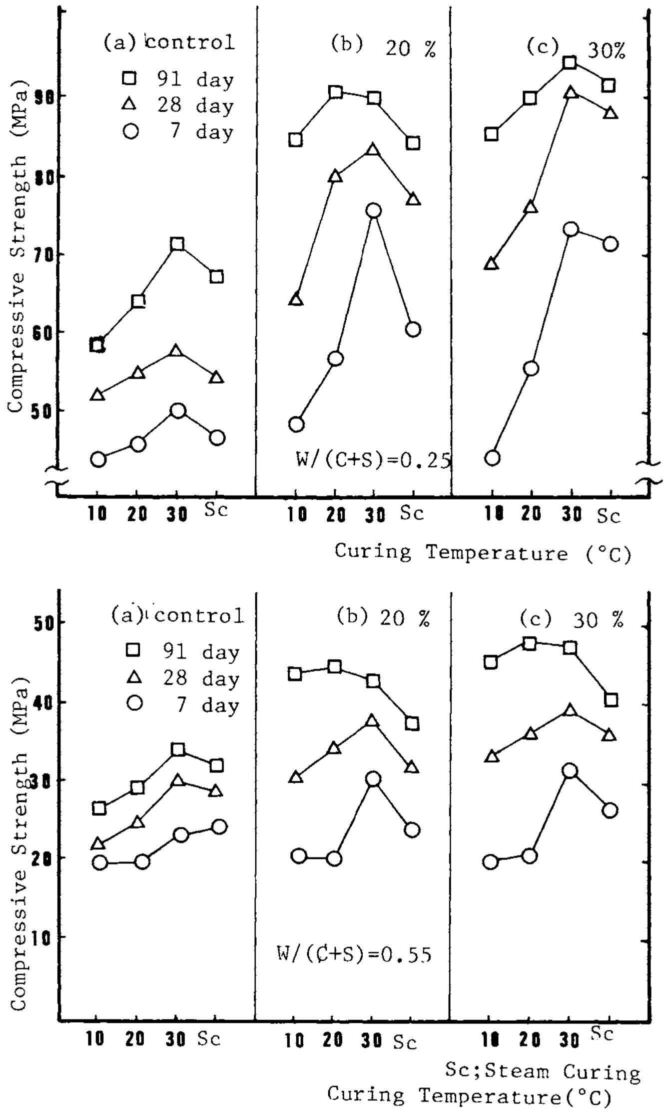

Fig. 5 Curing temperature versus compressive strength of concrete with and without silica fume
(a) control(0%silica fume) (b) 20% silica fume
(c) 30% silica fume

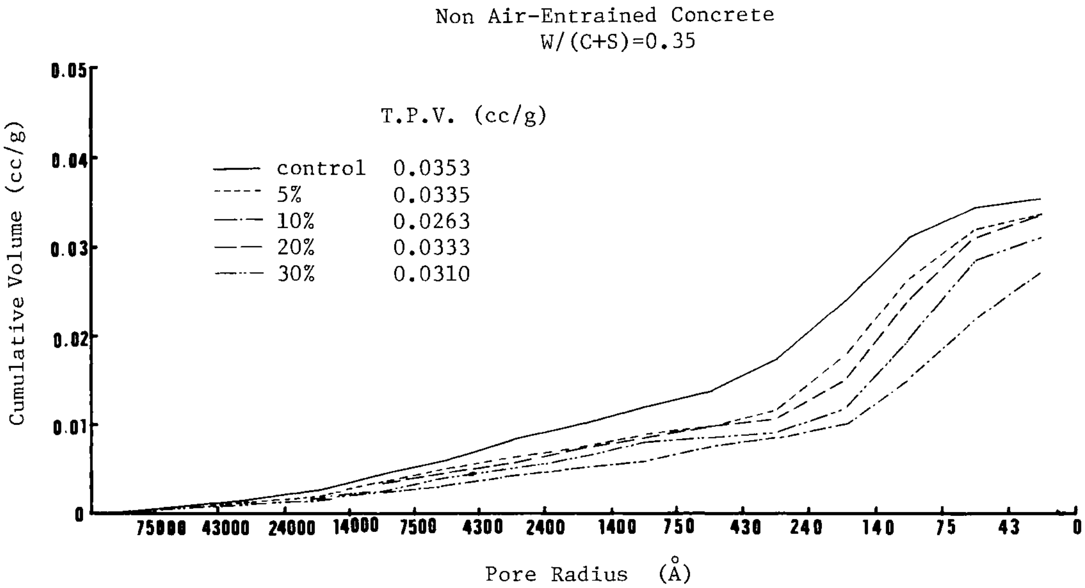

Fig. 6 Pore size distribution curves of concrete

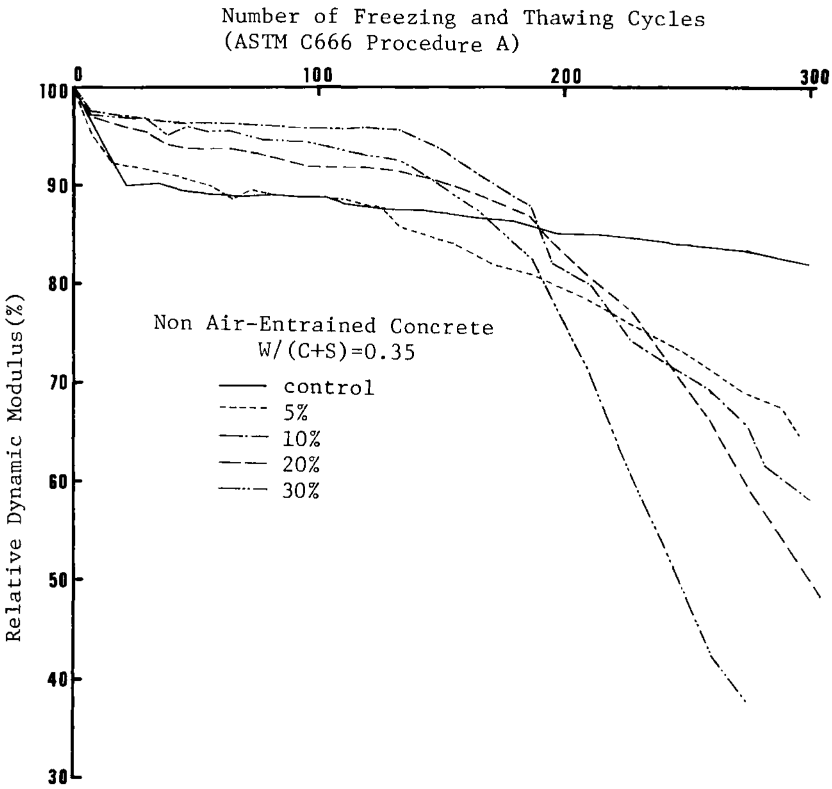

Fig. 7 Number of freeze-thaw cycles versus relative dynamic modulus of elasticity for non air-entrained concrete with and without silica fume