MINERAL BY-PRODUCTS AND FREEZE-THAW RESISTANCE OF CONCRETE

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The use of mineral by-products in concrete has increased considerably during the last few years. In the Nordic countries they are used both by the cement manufacturers and by concrete plants. The users are familiar with the effects of these products on the 28-day strength of concrete, but lack of knowledge does still exist of the effects on the durability of concretes. This article is aimed at giving information on the effects of ground granulated blast-furnace slag, pulverized coal fly ash, and condensed silica fume on the freeze-thaw resistance of concrete. This article is mostly based on two studies made at Oy Partek Ab's Development Centre in Pargas, Finland.

Keywords: Blast-Furnace Slag, Fly Ash, Silica Fume, Freeze-Thaw Resistance, Concrete

1. INTRODUCTION

Concrete can be damaged by freezing at two different stages. Early freezing occurs if the concrete is allowed to freeze soon after casting, when its strength is still insufficient to resist the stresses caused by freezing and expanding water. In this case one freezing cycle is enough to damage the structure of cement paste completely. Repeated freezing and thawing can also damage hardened concrete if the conditions are unfavourable. In this article only freeze-thaw resistance of hardened concete is discussed.

Mineral by-products can influence the freeze-thaw resistance of hardened concrete mainly by altering the pore structure of cement paste, by affecting the functioning of air-entraining agents or by changing the rate of strength development. The effects of blast-furnace slag, fly ash and silica fume have been studied by two test series. The first test series investigated normal concrete with a binder content of about 300 kg/m^3 and a 28-day strength about 35 MN/m^2. In the second test series a very good freeze-thaw resistance was to be achieved by the use of silica fume and a superplasticizer. In this series rapid hardening portland cement in the amount of 400 kg/m^3 was used.

2. NORMAL CONCRETE

2.1 Test Programme

The test programme for normal concrete was designed to simulate the manufacturing process of ready-mixed concrete plants. The concrete mixes were proportioned to achieve similar 28-day strength and were made at about the same consistency. The aggregate : cement ratio of concrete was 6,5 : 1, a composition commonly used in Finland. The binder content was approximately 300 kg/m^3. The properties of the materials are shown in Table 1, mix characteristics in Table 2, and the properties of hardened concrete in Table 3.

Air-entrained and non-air-entrained concretes were fabricated. PARMIX-L, a Finnish air-entraining agent was used, which is a colourless fluid containing up to 20 per cent of active ingredient, viz. polyglycolether sulphonate. This air-entraining agent has also a plasticizing effect.

Table 1. Properties of the Binders Used in the Experiments

	Cement	Blast-furnace slag	Fly ash	Condensed silica fume
Chemical composition %				
- CaO	61,9	36,2	7,7	0,63
- SiO_2	19,4	38,2	48,2	96,5
- Al_2O_3	5,0	10,3	23,1	0,24
- Fe_2O_3	2,3	0,5	10,3	0,06
- MgO	3,0	6,7	4,5	0,23
- Na_2O	0,88	1,0	0,86	0,27
- K_2O	0,96	0,71	2,4	0,63
- SO_3	1,32	0,02	1,0	0,21
- Loss on ignition	4,3	0,40	1,7	1,7
- Insoluble	4,1	1,2	76,3	96,4
Specific weight, kg/m^3	3100	2960	2340	2380
Specific surface area (Blaine), m^2/kg	377	457	441	5544
Sieve residue, %				
- 30 µm	37,9	9,3	26,9	0,0
- 40 µm	22,8	3,2	19,4	0,0
- 63 µm	13,3	1,1	12,7	0,0
Average particle size (Coulter Counter) µm	18,5	9,0	13,0	2,3

Table 2. Mix Characteristics and Properties of Fresh Concrete

Mix No.	Mix characteristics						Properties of fresh concrete		
	Cement kg/m^3	Slag kg/m^3	Fly ash kg/m^3	Condensed silica fume kg/m^3	PARMIX-L %	Water kg/m^3	Density kg/m^3	Slump mm	Air content %
C-1	295	-	-	-	-	180	2390	55	1,5
C-2	289	-	-	-	0,015	164	2330	60	3,7
C-3	287	-	-	-	0,025	159	2310	55	5,0
C-4	277	-	-	-	0,035	154	2230	70	7,0
B-1	198	99	-	-	-	172	2400	60	1,0
B-2	196	98	-	-	0,035	170	2370	60	2,0
B-3	191	96	-	-	0,055	157	2310	55	4,1
F-1	225	-	98	-	-	167	2400	60	1,2
F-2	220	-	96	-	0,035	151	2330	55	4,2
F-3	217	-	94	-	0,045	148	2300	60	5,2
F-4	214	-	93	-	0,055	150	2270	65	6,2
S-1	265	-	-	21	-	182	2380	55	1,5
S-2	256	-	-	21	0,035	153	2380	60	4,6

Table 3. Properties of Hardened Concrete

Mix No.	Comp. strength 28 d MN/m^2	Protective pore ratio	Freezing expansion µm/m	Frost-salt test Volume change, %		Critical degree of saturation 1)				Optical analysis	
				7 d	35 d	S_{CR}	t_{np}	S_{tnp}	t_{SCR}	Air 2) content %	Spacing factor mm
C-1	34,3	0,13	+55	34,7	4,3	0,905	8,4	0,93	0,001	0,76	0,303
C-2	33,3	0,19	-23	6,9	0,3	0,903	7,6	0,81	0,7	3,68	0,144
C-3	34,5	0,28	-24	4,2	0,5	0,926	6,0	0,75	9,5	6,37	0,130
C-4	31,8	0,39	-30	2,9	0,5	0,915	8,4	0,67	9735	7,93	0,114
B-1	36,6	0,09	+252	29,5	5,8	0,925	7,6	0,88	0,025	0,53	0,261
B-2	35,9	0,14	-4	6,3	2,9	0,944	7,5	0,87	0,5	1,57	0,175
B-3	34,7	0,25	-40	3,0	1,7	0,940	10,2	0,72	2680	5,06	0,142
F-1	35,6	0,13	+175	100,0	3,1	0,949	3,4	0,87	0,041	0,54	0,267
F-2	35,3	0,22	-74	6,3	1,9	0,860	11,2	0,77	0,2	5,03	0,144
F-3	34,7	0,28	-56	4,3	1,8	0,924	6,7	0,69	72	5,71	0,119
F-4	30,1	0,35	-73	3,8	2,0	0,932	8,7	0,66	133	7,92	0,092
S-1	40,9	0,12	+121	18,3	2,7	0,975	7,6	0,93	0,042	0,89	0,207
S-2	36,2	0,38	-61	2,9	1,2	0,965	9,4	0,72	971	4,66	0,150

1) S_{CR} is the critical degree of saturation,

t_{np} is time (h) at the nick point of the absorption curve,

S_{tnp} is the corresponding degree of saturation, and

t_{SCR} is the theoretical service life i.e. estimated time (years) for reaching S_{CR}.

2) The volume ratio of pores $d \leq 800$ µm in concrete.

2.2 Air Content

The target air content of air-entrained concretes was 4 per cent. The quantity of the air-entraining agent required was determined in a test series. The measured air contents of the mixes varied between 2,0 - 7,0 per cent, determined by the pressure method using the Toniporotest porosimeter in an 8 dm^3 volume. The results are shown in Figure 1.

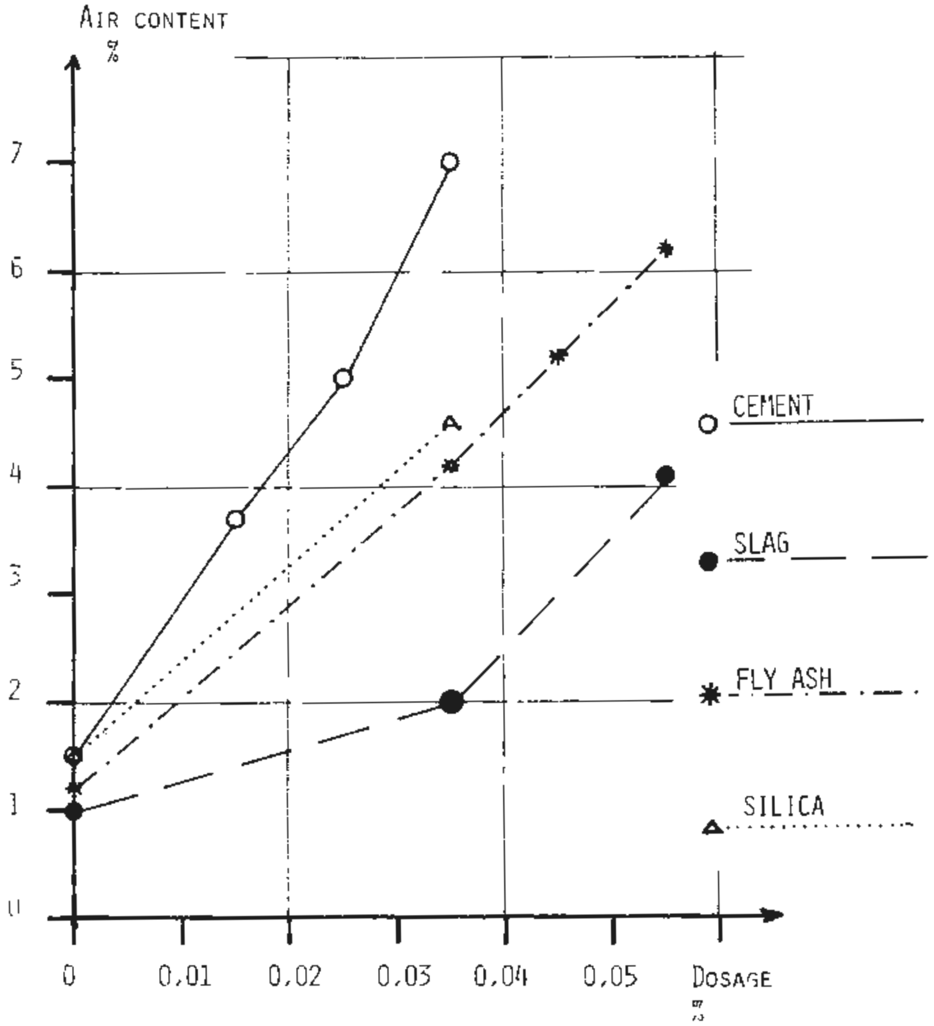

Fig. 1. The air content of fresh concrete as a function of the dosage of the air-entraining agent.

Considerable reduction of air content, relative to pure cement mixes, was found with the same dosage of air-entraining agent when slag, fly ash or silica was used. With fly ash and condensed silica fume this is to be expected, but not with blast-furnace slag which does not cause such a large decrease in the air content. One possible reason for these results is the fineness of the slag, which was greater than normal, and the other is the presence of interground coal in the slag, which might have formed in the mill.

2.3 Protective Pore Ratio

The protective pore ratio (P_r) was determined according to the Finnish standard SFS-4475. The protective pore ratio indicates the magnitude of the fraction of the pore volume that remains filled with air, when dried concrete is stored in water under normal pressure. The total pore volume is determined by saturation with water under an overpressure of 15 MPa. The standard requires a protective pore ratio $P_r \geq 0.20$ for frost resistant concrete and for severe exposure, $P_r \geq 0.25$.

The relationship between the air content of fresh concrete and P_r is shown in Figure 2. As far as cement, slag or fly ash are concerned the relationship is linear. However, the protective pore ratio of air entrained silica fume concrete was greater than what would have been expected on the basis of its air content.

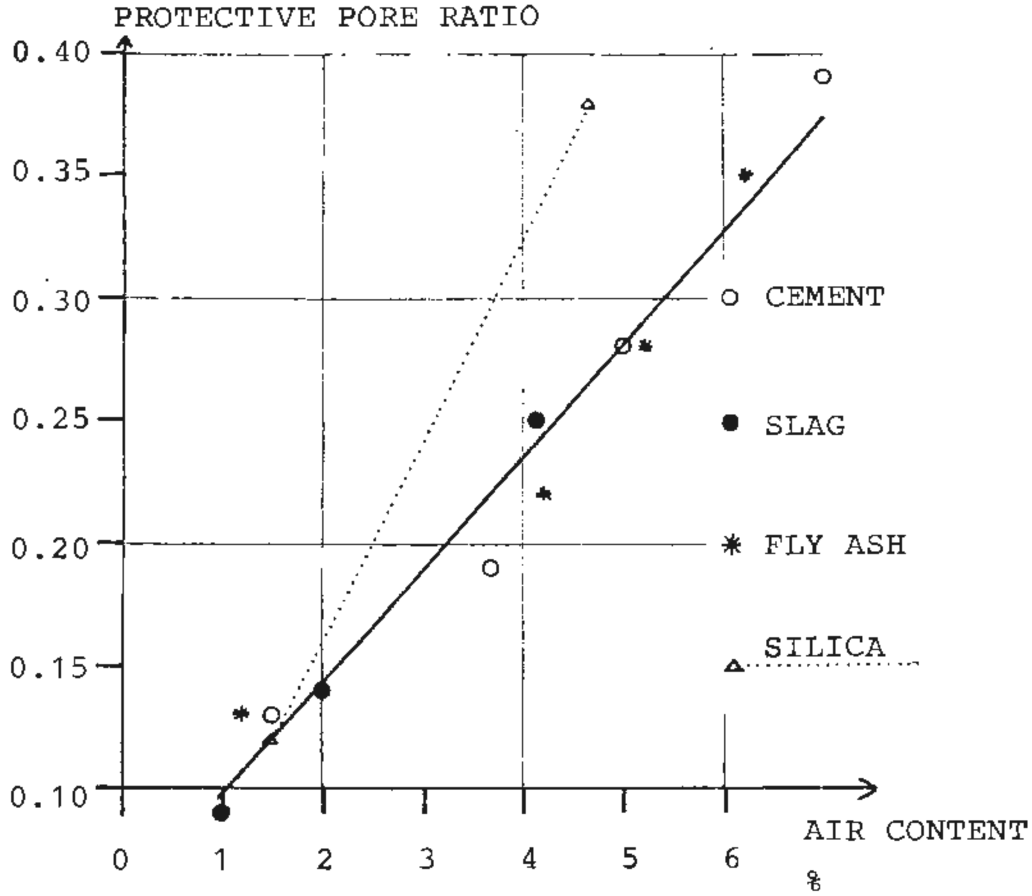

Fig. 2. The relationship between the protective pore ratio of hardened concrete and the air content of fresh concrete.

2.4 Freezing Expansion

The freezing expansion, i.e. the dilation index, was determined on test cylinders of 150 x 300 mm in size. It is calculated on the basis of changes in length, when the temperature is reduced from +20°C to -20°C in water-saturated specimen. For obtaining the thermal expansion coefficient of concrete, the length of the test cylinder was measured at a temperature of +20°C and +4°C. Then the test cylinder was cooled to a temperature of -20°C, and its length was measured. The dilation index was calculated as the difference between the change in length based on the thermal expansion coefficient of concrete and the verified change in length. According to the Finnish standards, a negative dilation index is the requirement to be fulfilled by a frost resistant concrete.

In Figure 3, the non-air-entrained concretes with slag, fly ash or silica fume showed poorer results than cement concrete. The air-entrained concretes made with slag, fly ash or silica, however, showed better frost resistance than the corresponding cement concretes.

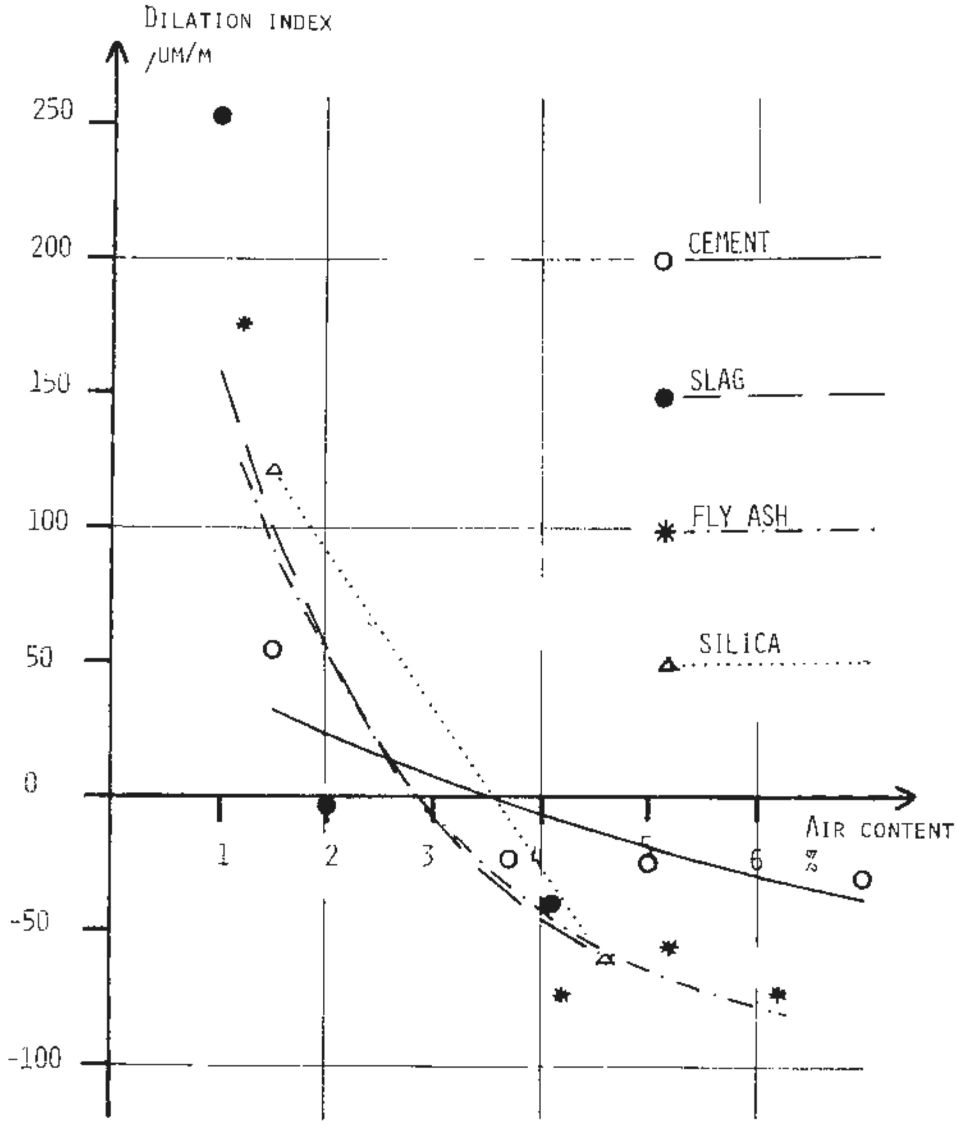

Fig. 3. The relationship between the freezing expansion, i.e. dilation index of concrete and the air content of fresh concrete.

2.5 Frost-Salt Test

Three test cubes of size 100 x 100 x 100 mm^3 were used for the frost-salt tests. The cubes were kept for one day in molds covered by a plastic sheet. Then the test specimens were cured under water. The cubes cured for 7 days were subjected to freeze-thaw test. The cubes to be tested at an age of 35 days were exposed to a relative humidity of 70% after 7 days under water. For water absorption these cubes were exposed to water at the age of 28 days, and were kept in water for 7 days until an age of 35 days, when the freeze-thaw test was started.

The freezing bath used was a saturated solution of sodium chloride, the temperature of which was -15°C. The thawing bath contained pure water at 20°C. The specimens were kept in the freezing bath for 8 hours and in the thawing bath for 16 hours. During weekends the specimens were kept in the thawing bath. The deterioration was measured after 25 freeze-thaw cycles by measuring the change in volume. The Finnish requirement for concrete pavings is that volume change must not exceed 5% after 25 cycles.

The results are shown in Figures 4 and 5. The figures indicate that non-air-entrained concretes have a very low frost-salt resistance at the age of 7 days. Condensed silica fume seems to improve this resistance. At the age of 35 days, the frost-salt resistance of all tested concretes is considerably higher.

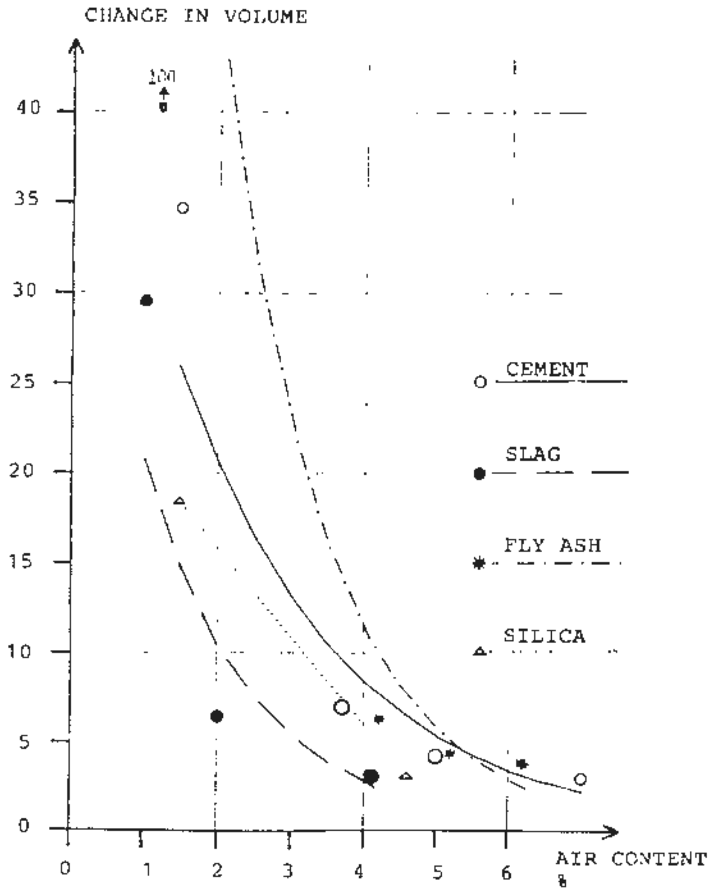

Fig. 4. Frost-salt test carried out on test specimens after 7 days of curing.

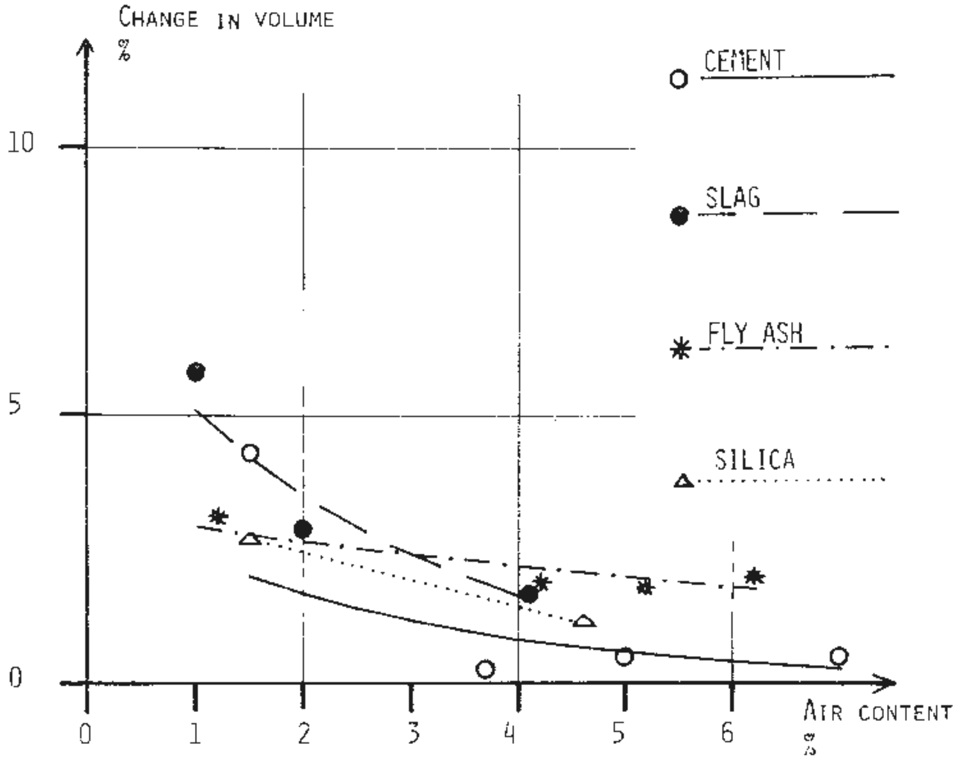

Fig. 5. Frost-salt test carried out on test specimens after 35 days of curing. The changes in volume after 25 freeze-thaw cycles.

2.6 Critical Degree of Saturation

The critical degree of saturation was determined by using the method developed by Fagerlund. Test specimens of abt. 50 x 100 x 100 mm^3 were sawn from beams 500 x 100 x 100 mm^3 in size. The beams were stored at a relative humidity of above 95% for 28 days. The sawn test specimens were dried for 7 days at a temperature of 50°C, after which they were vacuum saturated by water for 1 day. They were dried for different periods to attain a degree of saturation of 0,7...1,0. After the required degree of saturation was achieved, they were covered hermetically by a plastic film. They were subjected to six freeze-thaw cycles consisting of freezing at -15°C for 8 hours and thawing at +20°C for 16 hours. The change in the modulus of elasticity was determined by measuring the ultrasonic velocity through the test specimens. The test specimens were then dried at +105°C for determining the true degree of saturation.

The capillary water absorption was also determined on test specimens 50 x 100 x 100 mm^3 in size. After the initial drying at 50°C, the specimens were allowed to absorb water under normal pressure. The absorption of water was followed by weighing the specimens at specific intervals up to some months.

By studying the critical degree of saturation and the absorption rate of concrete, the theoretical service life can be predicted, i.e. that period during which concrete can be in continuous contact with water with out being damaged during freezing. Because concrete normally comes into contact with air of varying relative humidities, the real service life of concrete is usually longer than that based on the theoretical prediction. Concretes can, however, be ranked based on their theoretical service lives.

All values for the critical degree of saturation (Table 3) are higher than those expected on the basis of earlier investigations made by Fagerlund. The freezing temperature used in these tests, which was no lower than -15°C, may be a contributive factor for these higher values.

Except for one mix, critical degrees of saturation for slag, fly ash and silica fume concretes are higher than those with cement concretes. The critical degrees of saturation of concretes containing condensed silica fume seem to be higher than those of other concretes. The air content of fresh concrete seems to have no systematical influence on the critical degree of saturation.

The capillary pores of all concretes are filled between 3,4... 11,2 hours, at which time the peak point of the absorption curve is reached. The average time was 7-9 hours. Slag, fly ash, silica fume or the air content has no systematical effect on capillary absorption.

The air content, however, has an effect on the degree of saturation, which is reached before the peak point of the absorption curve. It can be seen that the degree of saturation decreases as the air content is increased. Slag, fly ash and silica fume concretes showed slightly lower degrees of saturation at the peak point of the absorption curve than corresponding cement concretes.

The air content has also a very significant influence on the estimated time for reaching the critical degree of saturation. The theoretical service life has been calculated assuming that water absorption is logarithmically dependent on the time of absorption after reaching the peak point. In this calculation an extrapolation is needed for the more frost resistant concretes, and also a logarithmic scale is used and hence even small errors in test results may cause quite a large error in the predicted service life.

In Figure 6 the relation between the theoretical service life and the air content of concrete is shown. These results would indicate that a certain increase in the air content would prolong the theoretical service life of concrete tenfold. In these concretes the required increase in air content would be 0.8 per cent for cement concretes, 0.6 per cent for slag concretes, 1.3 per cent for fly ash concretes, and 0.6 per cent for silica fume concretes. Results also show that slag and silica fume concretes have a higher freeze-thaw resistance than corresponding fly ash or cement concretes.

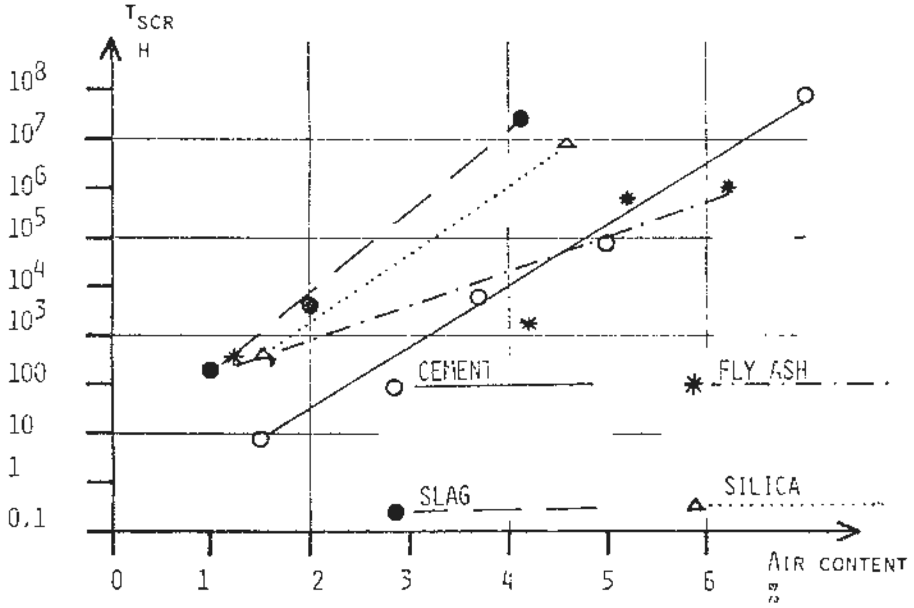

Fig. 6. The relation between theoretical service life (t_{SRC}) and the air content of fresh concrete.

2.8 Optical Analysis

For optical analysis of the pore structure two specimens with a polished surface area of 5600 mm^2 were prepared from the concretes. As many as 325 spots of area 2.5 mm^2 were analyzed.

The spacing factor of air bubbles showed a good relationship with the air content of concrete (Figure 7). Results for slag, fly ash or silica fume concrete fall on the same line.

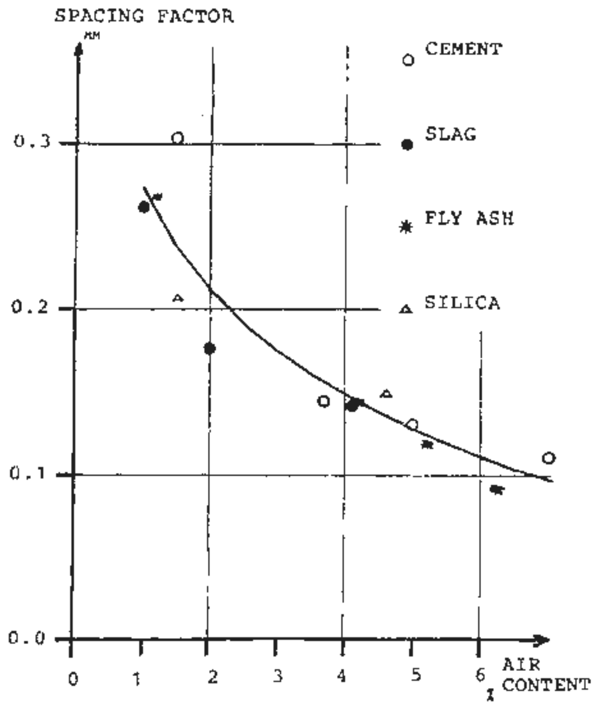

Fig. 7. The relation between the spacing factor and the air content of fresh concrete.

2.8 Relative Frost Resistance

Different test methods give differing results of the ranking order. This may be the reason why earlier investigations have given conflicting results. If the freeze-thaw resistance of these concretes is considered to correlate with the total of ranking numbers in different tests, the ranking order would be as follows:

- C-4: Cement concrete, 7,0% air-entrained
- S-2: Silica fume concrete, 4,6% air-entrained
- F-4: Fly ash concrete, 6,2% air-entrained
- B-3: Slag concrete, 4,1% air-entrained
- F-3: Fly ash concrete, 5,2% air-entrained
- C-3: Cement concrete, 5,0% air-entrained
- F-2: Fly ash concrete, 4,2% air-entrained
- C-2: Cement concrete, 3,7% air-entrained
- B-2: Slag concrete, 2,0% air-entrained
- S-1: Silica fume concrete, non-air-entrained
- F-1: Fly ash concrete, non-air-entrained
- C-1: Cement concrete, non-air-entrained
- B-1: Slag concrete, non-air-entrained

3. SUPERPLASTICIZED SILICA FUME CONCRETE

3.1 Test Programme

The purpose of this study was to develope a more frost resistant concrete for the edge beams of road bridges. These beams are imposed to very severe freezing and thawing conditions, particularly where salt is used to thaw snow and ice off the road. When normal air-entrained concretes have been used for these beams, they have had to be repaired repeatedly at intervals of a few years.

In this test series the basic mix was chosen to contain 400 kg/m^3 of rapid hardening portland cement and 2% of melamin based superplasticizer (Melment L-10). The slump of the fresh concrete was 15 ± 1 cm, and it was kept constant from mix to mix by varying the water content. A total of 16 different mixes were made. In these mixes the silica content was 0%, 4%, 8%, and 16% of the cement content, and the air-entraining agent (Parmix-L) was used in the amounts of 0%, 0.02%, 0.04%, and 0.08% of the cement content. The concrete mixes are shown in Table 4.

The freeze-thaw resistance of concrete was determined by using the protective pore ratio, the frost-salt test described above, and a freeze-thaw test. In the freeze-thaw test specimens are frozen in air at a temperature of -20°C and thawed by pure water at a temperature of +20°C. An automatic freezing and thawing machine was used to enable 3 freezing cycles a day. Beams of 100 x 100 x 500 mm^3 size were used as test specimens. The flexural and compressive strengths were tested before freezing and thawing and after 200 freeze-thaw cycles. Reference beams were kept in water (+20°C) during the freeze-thaw test. The strength results are shown in Table 5.

Table 4. Mix Characteristics and Properties of Concrete in Test Series II.

Marks	Mix Characteristics						Concrete Properties			
	Cement kg/m^3	Aggregate kg/m^3	Water kg/m^3	Silica Fume %-cement	Melment L-10 %-cement	Parmix L %-cement	Slump	Air Content %	Compressive strength MN/m^2 28 d	91 d
SI-1	404	1816	172	0	2.0	0	14.0	1.6	51.0	51.5
SI-2	395	1779	182	4	2.0	0	16.0	1.5	52.0	63.6
SI-3	390	1757	183	8	2.0	0	14.0	1.7	56.1	65.8
SI-4	375	1688	209	16	2.0	0	15.0	1.3	54.6	60.9
SI-5	385	1732	155	0	2.0	0.02	16.0	5.8	41.6	51.3
SI-6	388	1745	154	4	2.0	0.02	16.0	5.3	49.1	56.8
SI-7	382	1721	157	8	2.0	0.02	14.0	5.3	53.1	58.5
SI-8	376	1691	195	16	2.0	0.02	14.0	2.4	55.7	59.9
SI-9	378	1700	134	0	2.0	0.04	15.5	8.1	42.0	47.7
SI-10	378	1699	139	4	2.0	0.04	15.0	7.2	45.4	52.4
SI-11	369	1661	152	8	2.0	0.04	16.0	6.9	46.8	56.9
SI-12	363	1634	167	16	2.0	0.04	14.0	5.0	53.8	56.5
SI-13	362	1630	130	0	2.0	0.08	16.0	10.5	39.9	48.0
SI-14	374	1684	129	4	2.0	0.08	14.5	7.7	44.1	51.1
SI-15	368	1656	139	8	2.0	0.08	15.5	7.8	45.2	51.6
SI-16	359	1617	159	16	2.0	0.08	14.5	6.8	44.8	48.3

Table 5. Results of Frost Resistance Tests

Marks	Protective pore ratio	Modified protective pore ratio	Freeze-Thaw Test						Salt-Frost Test, decrease in volume (%)				
			Compressive strength (MN/m^2)			Flexural strength (MN/m^2)			cycles				
			before test	after 200 cycles	reference beams	before test	after 200 cycles	reference beams	10	25	50	75	100
SI-1	0.18	0.18	22.5	56.0	53.0	5.65	6.33	5.57	0.3	3.2	6.8	13.2	20.3
SI-2	0.17	0.17	44.5	34.5 1)	52.5	6.01	1.84 1)	7.17	0.1	0.2	1.1	3.4	7.2
SI-3	0.39	0.23	47.5	33.0 1)	56.0	6.05	0.92 1)	8.09	0.1	0.0	0.0	0.3	1.0
SI-4	0.30	0.24	43.5	- 1)2)	52.5	6.49	- 1)2)	8.29	0.0	0.1	0.0	0.2	0.4
SI-5	0.27	0.27	36.5	50.0	49.5	5.57	5.09	5.97	0.0	0.3	1.4	4.2	8.6
SI-6	0.43	0.35	41.5	45.5	50.5	6.45	5.17	5.37	0.0	0.0	0.2	2.2	4.2
SI-7	0.51	0.34	37.5	49.0	48.5	6.29	5.01	5.65	0.0	0.0	0.0	0.3	0.8
SI-8	0.51	0.29	44.5	54.5	53.0	8.13	4.37	6.69	0.0	0.0	0.0	0.0	0.0
SI-9	0.47	0.46	31.0	38.5	41.0	5.25	4.61	4.13	0.1	0.2	0.9	5.9	10.8
SI-10	0.56	0.47	38.5	47.0	40.0	6.85	7.17	7.37	0.0	0.0	0.0	2.7	5.3
SI-11	0.63	0.42	37.5	52.0	46.0	6.49	6.65	6.85	0.0	0.0	0.0	0.5	2.2
SI-12	0.65	0.36	49.0	50.5	47.5	6.85	7.85	8.05	0.0	0.0	0.1	0.2	0.4
SI-13	0.46	0.46	30.5	43.0	41.5	7.09	5.85	7.05	0.3	0.8	2.9	7.7	12.5
SI-14	0.60	0.46	37.5	49.0	43.0	6.01	6.53	8.09	0.0	0.0	0.0	0.7	3.0
SI-15	0.71	0.46	34.0	41.0	43.0	6.93	6.65	7.93	0.1	0.0	0.0	0.7	1.8
SI-16	0.75	0.42	40.0	42.5	41.5	5.81	6.13	7.17	0.1	0.1	0.0	0.2	0.3

1) The specimen was in contact with water during freezing, too.

2) The specimen deteriorated after 150 cycles.

3.2 Protective Pore Ratio

Protective pore ratio results show that the use of condensed silica fume increases the values of this ratio considerably. From Figure 8 can be seen that the protective pore ratio no longer correlates with air content, but a higher amount of silica fume gives a higher protective pore ratio at the same air content of the fresh concrete.

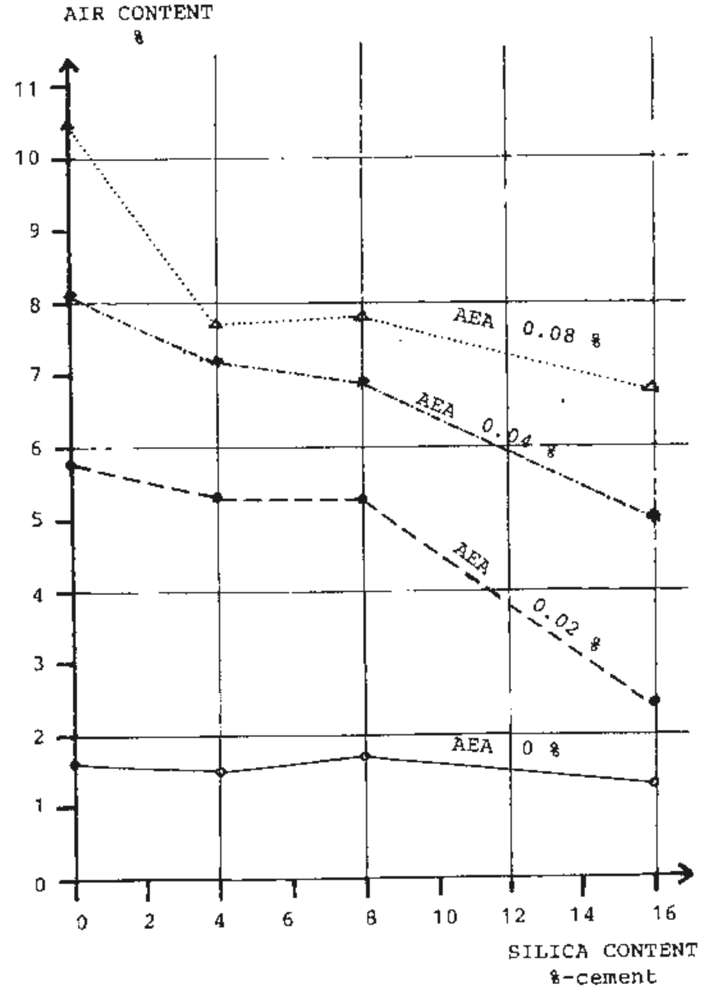

Fig. 8. The air content of silica fume concretes, AEA = air-entraining agent (PARMIX L).

It was also noticed that introduction of silica fume into the concrete made it much less absorbent. The amount of water sucked into the dried concrete under normal pressure was decreased from 117 kg/m^3 of the basic concrete to a minimum of 52 kg/m^3 of concrete SI-16. It was also noticed that the absorbed water amounts of the silica fume concretes were less than those water amounts dried away from the specimens during drying at +105°C. This indicates that this test method is not valid for silica fume concrete, because the amount of water that can be in the pore system of concrete is greater than the amount it sucks during this test. An attempt to eliminate this error was made by calculating the protective pore ratio based on the water amount that could be dried out from the concrete. These results are also shown in Table 5 as "modified protective pore ratio".

All results obtained for protective pore ratio and "modified protective pore ratio" showed a very good frost resistance of air-entrained silica fume concretes. Only for non-air-entrained concretes SI-1...SI-4 a value smaller than 0.25 was obtained, which is considered to be the lower limit for frost resistant concrete under severe conditions.

3.3 Freeze-Thaw Test

In the freeze-thaw test all concretes, except for SI-2, SI-3 and SI-4, showed good frost resistance. These three mixes were all silica fume concretes with no air-entrainment. It was, however, noticed that these three specimens were also misplaced into the automatic freezing machine so that they were in contact with water during freezing, too. That is why these results cannot be compared with the other test results.

3.4 Frost-Salt Test

This test was considered to be the most important in the test series, because this study was aimed at investigating salt-frost resistance. For that reason this test was extended up to 100 cycles instead of the normal 25 cycles.

The results obtained clearly showed the great improvement of the salt-frost resistance thanks to silica fume. The decrease in volume after 25 cycles varied from 3.2% for basic concrete to 0.0% for many silica fume concretes. This shows that the basic mix without silica fume and air-entrainment also has a very good salt-frost resistance, because the normal criterion for this test is a volume decrease less than 5%. This good salt-frost resistance of basic concrete can probably be explained by the low water cement ratio (0.44), and the use of a superplasticizer, which together may have caused a favourable pore system and a dense cement paste.

However, the basic concrete did deteriorate quite badly after 100 test cycles. The volume decrease was then 20.3%. i.e. one fifth of the volume had been scaled off. The concretes containing only air-entraining agent showed better salt-frost resistance, the volume decrease being 8.6%, 10.8% and 12.5%, when the dosages were 0.02%, 0.04% and 0.08% respectively.

When silica fume was added to a mix, and the other components were kept constant, it resulted in a decrease in the air content as seen in Figure 9. However, in all cases the salt-frost resistance was greatly improved. For example, with a dosage of air-entraining agent of 0.02% of the cement by weight, the air contents were 5.8%, 5.3%, 5.3% and 2.4% at a silica fume content of 0%, 4%, 8% and 16% respectively. The volume decrease after 100 cycles were 8.6%, 4.2%, 0.8% and 0.0%. The development of these volume decreases is shown in Figure 10.

Figure 11 illustrates the volume decrease after 100 cycles of salt-frost test in respect of the silica fume amount. As can be seen from the figure the salt-frost resistance is largely dependant on the silica fume content and much less dependant on the amount of air-entraining agent, i.e. air content.

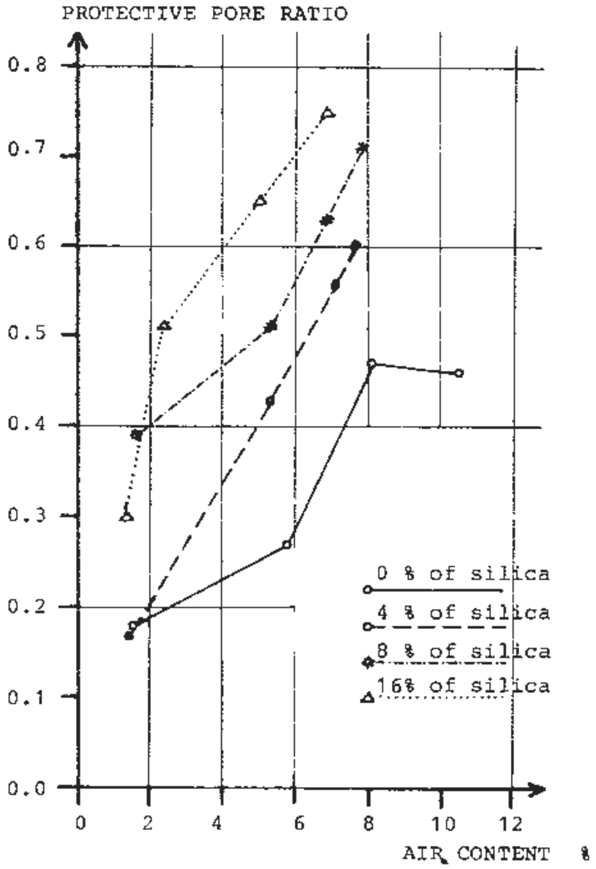

Fig. 9. Protective pore ratio as a function of the air content of fresh concrete

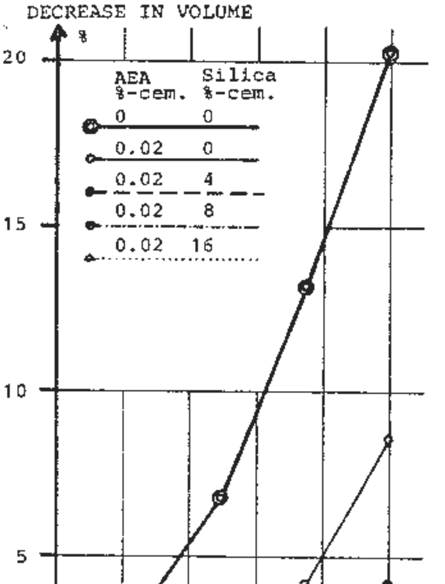

Fig. 10. Volume decrease of concretes SI-1, SI-5, SI-6, SI-7 and SI-8 as a function of the number of cycles in the salt-frost test

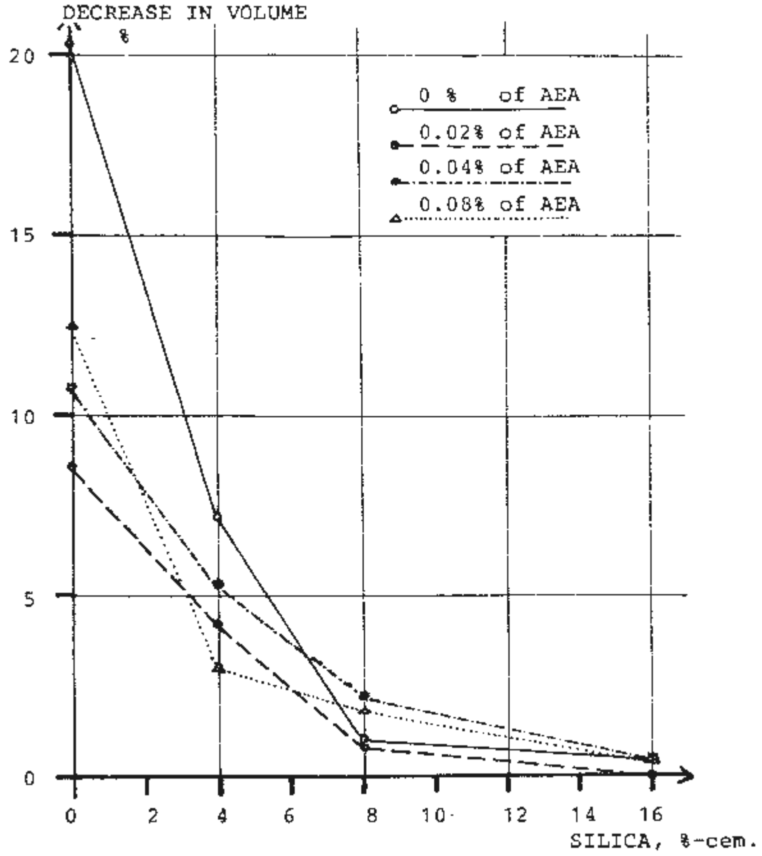

Fig. 11. Volume decrease after 100 cycles of salt-frost test as a function of silica content

4 CONCLUSIONS

These test series have showed that different test methods give different results. This should also be taken into account when new materials are tested, and particularly when indirect test methods are used. However, the following conclusions can be drawn about the influence of mineral by-products upon the freeze-thaw resistance of concrete.

1. All mineral by-products decrease the effect of air-entraining agents, and thus a greater dosage is needed for a given air content.

2. Condensed silica fume improves the freeze-thaw resistance of concrete, and the salt-frost resistance in particular. This is also true for a constant dosage of an air-entrained agent, i.e. decreased air content.

3. Blast-furnace slag might improve freeze-thaw resistance slightly when the air content and strength of concrete are kept constant.

4. Fly ash does not decrease freeze-thaw resistance if the air content and strength of concrete can be kept constant.

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