FIELD STUDY ON THE EFFECTS OF ADDITIONS ON THE SALT-SCALING RESISTANCE OF CONCRETE

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ABSTRACT

The use of ground granulated blast-furnace slag and silica fume as additions in concrete under frost and salt actions has been recommended because of excellent behavior in laboratory tests at the age of 28 days. However, some tests made with artificially aged concretes containing additions have indicated a decreased durability compared with tests without ageing. This has been thought to depend on the pore structure becoming coarser during carbonation of such concretes. In order to study this phenomenon in actual structures a small field study was performed.

The results of this field study indicate that the ageing of slag or silica concrete under actual outdoor conditions in Finland does not influence the salt-scaling resistance of concrete. However, this phenomenon has to be studied in still more detail.

Keywords: Concrete, durability, frost, additions, slag, fly ash, silica

1 INTRODUCTION

Additions can influence the frost-resistance of hardened concrete by affecting the functioning of air-entraining agents, by altering the stability of entrained air, by changing the rate of strength development, by affecting the pore structure of hardened cement paste and, in the case of deicing salts, by reducing the chloride permeability of the concrete. Ageing of concrete containing additions may also result in different pore structure than ageing of portland cement concrete.

All additions increase the dosage requirement of the air-entraining agent, to give a desired amount of entrained air. However, it appears that the air void parameters are not influenced by the use of additions, as long as the proper amount of air is entrained into the concrete. The stability of air-entrainment does not seem to be affected by the use of additions.

Carbonation in slag concrete is more rapid than in normal concrete. Carbonation also results in a coarser pore structure of slag cement paste, while the opposite is true for portland cement paste. This is why the frost-resistance of slag concrete is considered somewhat skeptically. The influence of carbonation on fly ash or silica concretes have not been as great as on slag concrete. Repeated drying and wetting could have an effect on the pore structure of pastes made with additions, but this has not been studied enough to draw final conclusions about how much this behavior differs from that of portland cement concrete.

Earlier tests made with additions give no clear answers as to whether these materials are beneficial or harmful to the frost-resistance and salt-scaling resistance of concrete. Results pointing in both directions have been gained. It seems that negative results, have in many cases been due to extreme amounts of additions used in concrete. This being the case, one should have to limit the allowed amounts of these materials in frost-resistant or salt-scaling resistant concrete. It could seem possible, considering results presented in literature, to limit the amounts of ground slag, fly ash and silica to maximums of 50%, 25% and 10% of total binder content, respectively. It seems also that the use of slag or silica in such limited amounts could give a positive influence to frost-resistance of concrete, while fly ash does not have any greater advantages to offer.

The effects of condensed silica fume, ground granulated blast furnace slag and pulverized coal fly ash have been studied by laboratory and field tests. The first laboratory test series investigated normal concrete with a binder amount of about 300 kg/m^3 and a 28-day strength of about 35 MPa. The second laboratory test series aimed at a very good frost-resistance of concrete under the influence of deicing agents. In this series, silica fume and a superplasticizer were used together with an air-entraining agent. The results of these tests have earlier been reported in /1/. Some important conclusions of these tests are summarized also in this report.

The possible effects of ageing on the frost-resistance of slag and silica concretes were studied under field conditions over a period of 5 to 7 years. These tests are reported below.

2 LABORATORY TESTS

The laboratory tests have been made in two different stages. In the first series, the frost-resistance of normal strength concrete was studied. Here the water/cementitious ratio was about 0.55 and the compressive strength at 28 days age was about 35 MPa. Slag, fly ash and silica amounts of normal ready-mixed concrete practice were used.

In the second series, silica concrete with a higher compressive strength level of about 45 to 55 MPa was studied. This series was based on the good results obtained with silica concrete in the first series. This test series concentrated on salt-scaling resistance, because this seems to be the largest problem for concrete in edge beams of bridges. These tests have been reported in more detail earlier in /1/ and in /2/. Only some important conclusions of these tests are repeated here.

In the first series, it could be seen that different test methods give differing results of the frost-resistance of concrete. From the noticeable differences it could be concluded that the test methods measure different properties of concrete, although they are all meant to evaluate the frost-resistance of concrete. However, when one ranked the concretes in different tests and calculated the sum of the ranking numbers the correlation between the sum of ranking numbers and the air content of fresh concrete was found to be very high. The biggest difference from this correlation was the air-entrained silica concrete.

In the second series, the best correlation of the salt-scaling results was found for the silica addition in the concrete. These results are shown in Figure 1. The results indicate that silica addition clearly improves the salt-scaling resistance of concrete. Also, the effect of silica on the salt-scaling resistance was found to be greater than its effect on the strength of concrete. The results also indicate that silica is more effective in increasing salt-scaling resistance than air-entrainment. According to these results, it could be claimed that no air-entrainment is necessary for silica concrete with a low water/cement-ratio. Here one has to remember, however, that the salt-scaling tests were done with small cubes carefully manufactured, vibrated and cured and these results can be misleading in actual practice.

All concretes, except the silica concretes without air-entrainment, showed good frost-resistance in freezing and thawing without deicing salts (Figure 2.) The test specimen of concrete containing 16% silica did actually deteriorate after 150 cycles. Also specimens containing 8 and 4% silica had clear cracks forming from the bottom end of these beams after 100 cycles of freeze-thaw test. When these specimens were monitored more closely, it was found out that they had been put into the freeze-thaw machine so that their bottom end was in contact with water when freezing occurred while other specimens were not. This being the case and

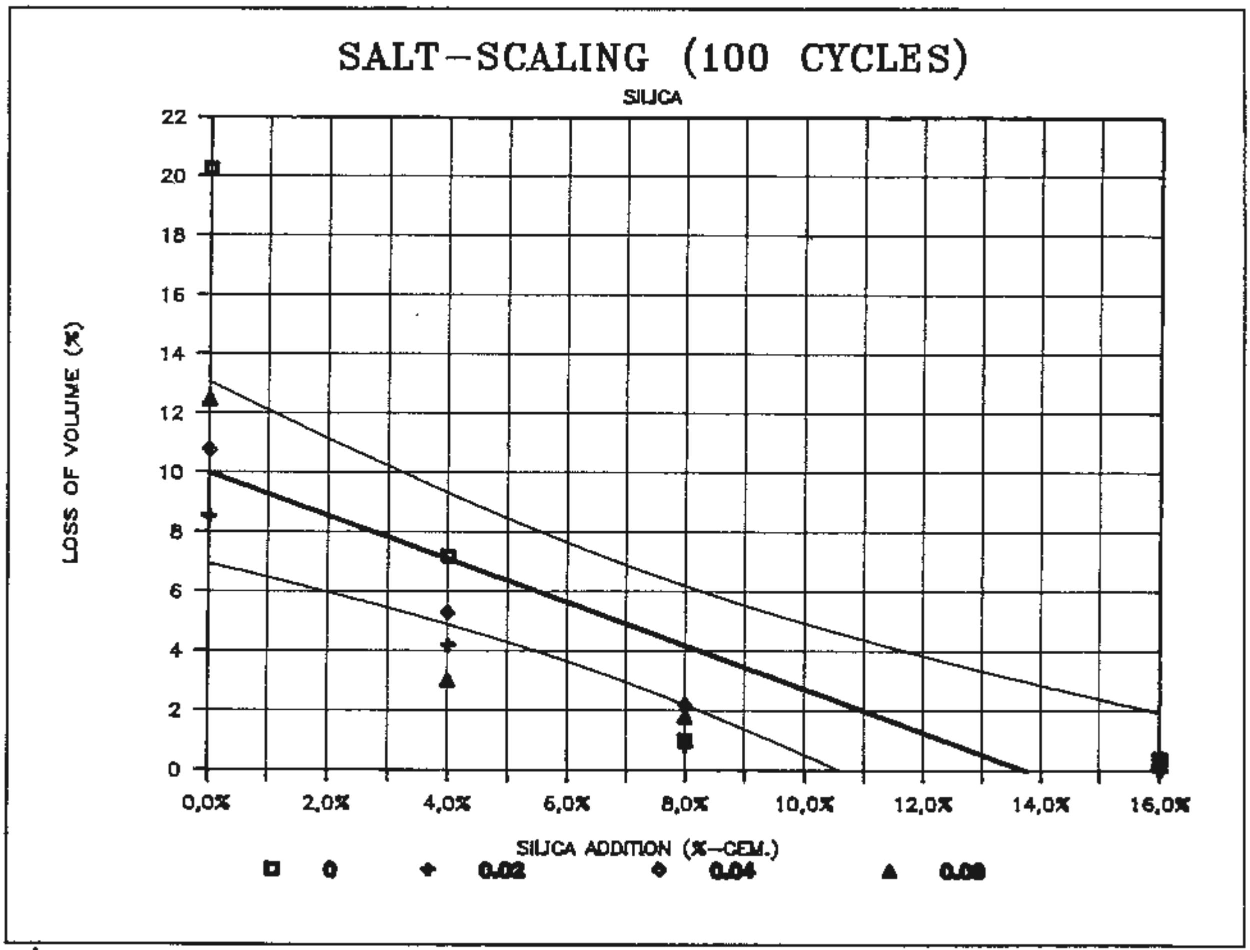

Figure 1. The volume loss of concretes after 100 cycles of salt-scaling test as a function of silica dosage. Test series II. 0, 0.02, 0.04 and 0.08 denote the dosage of Parmix L as % by weight of cement.

because the cracking started at this same end of the specimens, it can be concluded that these results are not comparable with the results of other specimens. However, it must be noticed that non air-entrained silica concrete continuously in contact with water is vulnerable to frost attack.

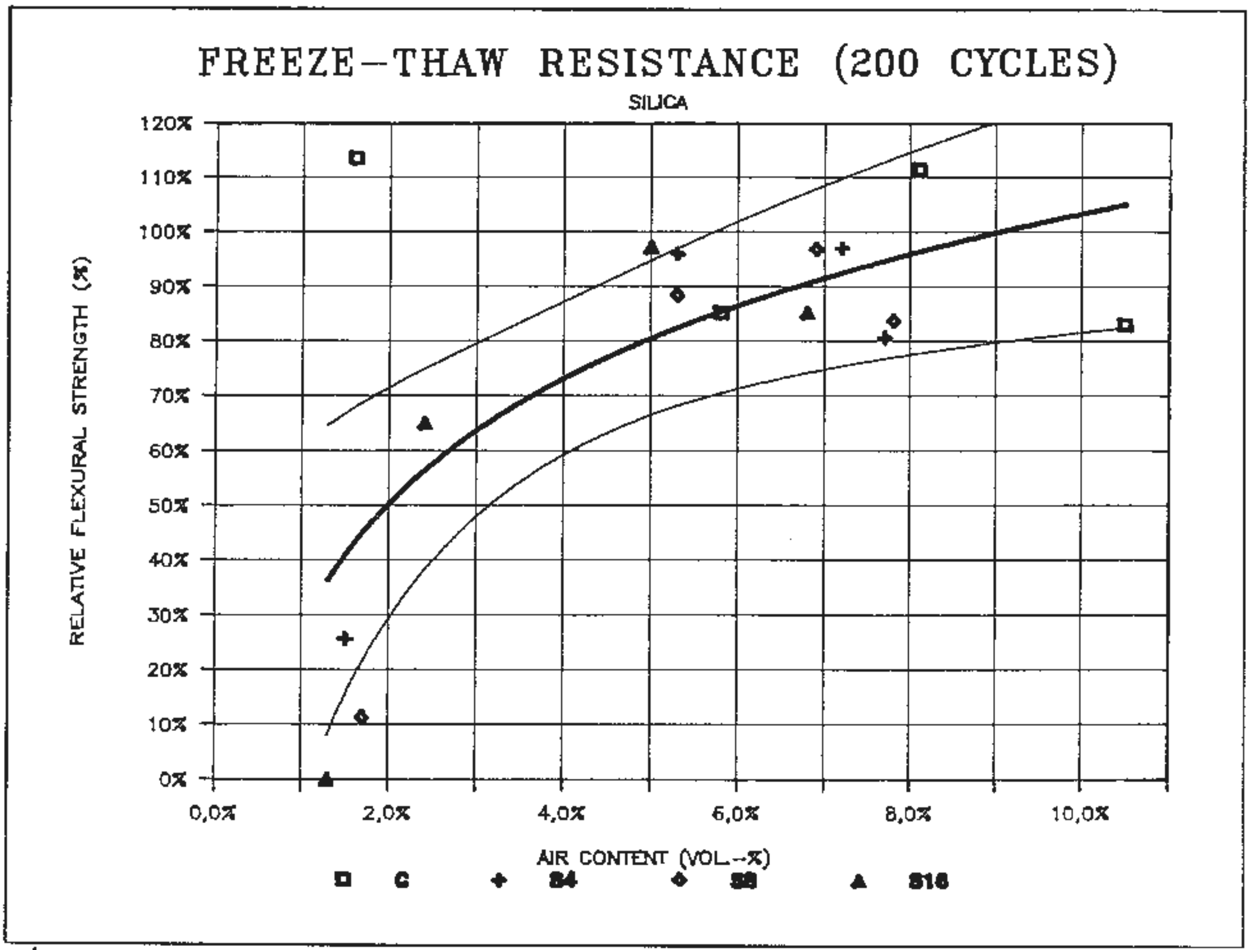

Figure 2. Flexural strength of concrete after 200 cycles of freeze-thaw test compared with reference beams stored in water. C denotes cement, S4 silica 4%, S8 silica 8% and S16 silica 16%. The regression curve with 95% confidence limits is also shown.

3 FIELD TESTS

After the laboratory tests had been performed, the question about the ageing of by-product concretes and its importance to frost-resistance was raised. In order to study this phenomenon in practical conditions, it was decided to take some cores out of concrete structures made with slag and silica. No fly ash concretes were studied here, because fly ash is not usually used in frost-resistant concretes in Finland. However, some of the concretes in this series were made with standard cement, which contains fly ash up to 25% by weight of cement.

3.1 Test methods

The Finnish test methods for studying frost-resistance and salt-scaling resistance differ to some extent of those in practice in other Nordic countries. The most commonly used method is the indirect test of measuring the protective pore ratio (Standard SFS-4475). The test specimens are first dried to constant weight at a temperature of 105 °C. After drying. the specimens are immersed in water at normal pressure and they are allowed to absorb water until gaining equilibrium, i.e. the weight change is less than 0.05% per day. The specimens are transferred to pressure equipment, where water is pressed into them at an overpressure of 15 MPa. The protective pore ratio is calculated by dividing the water amount pressed into the concrete at overpressure, by the total water amount absorbed and pressed into the concrete. Concrete is considered to be frost-resistant under normal outdoor conditions and under salt-scaling conditions if the protective pore ratio exceeds 0.20 or 0.25, respectively.

The salt-scaling resistance tests are made according to SFS-5449. Here, the freezing bath is a saturated solution of sodium chloride at a temperature of -15 °C. The thawing bath consists of pure water at a temperature of +20 °C. The test specimens are transferred to the freezing bath directly from the thawing bath and the freezing lasts for 8 hours. Then, the specimens are transferred quickly to the thawing bath for 16 hours. During weekends and holidays the specimens are kept in the thawing bath. The scaling of the specimens is measured by weighing them in air and water and calculating the loss of volume. The concrete is considered to be salt-scaling resistant if the loss of volume after 25 cycles is less than 3.3%.

3.2 Slag concrete

Slag has been used in concrete road building in Finland as a cement replacement, because slag is cheaper than cement, it gives better flexural strength and also better salt-scaling resistance of concrete. The first test road with slag replacement was built in Pargas during summer 1982. Here several different mix designs were tested. The ones considered here were the mixes, which had the same total binder amount and the same air content. The first one of these was made using portland cement only and the second using a slag replacement of two thirds of the total binder amount.

The road was built using a slip-form paver. Before and during the paving, tests were made on air content, compressive strength, protective pore ratio and flexural strength of concrete. Compressive strength of concrete was also tested from cores taken out from the road by diamond drilling. No freeze-thaw or salt-scaling tests were performed at the time. Results of these tests and the mix design of these concretes are shown in TABLE I.

In late summer 1989, cores with a diameter of 100 mm were drilled in both concretes. Six cores were taken from both concrete types.

TABLE I. Mix design and test results of slag concrete in field test. Concrete road at Pargas.

	Concrete	
	2 (Cement)	6 (Slag)
Mix proportions kg/m^3		
Cement	350	140
Slag	0	210
Water	147	147
Parmix L %-cem.	0.055	0.055
Melment L10 %-cem.	3.0	3.0
Properties of fresh concrete		
Air content %	3.4	3.2
Slump mm	10	50
Properties of hardened concrete		
Compressive strength MPa		
- cast specimens		
-- 1 d	23.2	5.9
-- 3 d	32.0	15.3
-- 7 d	38.3	37.5
--28 d	43.8	50.7
- drilled cores		
--91 d	49.0	71.2
-- 1 year	61.4	73.0
Flexural strength MPa		
- 28 d	5.9	6.5
- 91 d	6.8	7.7
Protective pore ratio %	-	17

From these specimens one was used to measure the compressive strength, two for determining the depth of carbonation and optical analysis of pore structure and three for the salt-scaling resistance measurements. The measurements of carbonation depth and the optical analysis were carried out at Technical Research Center of Finland at Concrete and Silicate laboratory /3/. The results are shown in TABLE II.

The results show that slag concrete is after 7 years of outdoor exposure less carbonated than corresponding cement concrete. Its compressive strength is also over 10 MPa higher than that of

TABLE II. Test results from the concrete road at Pargas after 7 years of outdoor exposure.

	Concrete	
	2 (Cement)	6 (Slag)
Mix proportions kg/m^3		
Cement	350	140
Slag	0	210
Water	147	147
Parmix L %-cem.	0.055	0.055
Melment L10 %-cem.	3.0	3.0
Properties of concrete after 7 years exposure		
Depth of carbonation mm	0.4 - 15	0.2 - 5
Air content %	2.3	3.4
Spacing factor mm		
-Powers	0.18	0.21
-pores <800 μm	0.13	0.11
Compressive strength MPa	57.5	70.0
Salt-scaling resistance		
Volume loss %		
- 10 cycles	0.8	0.2
- 25 cycles	1.8	0.2
- 50 cycles	5.5	1.0
- 75 cycles	11.2	2.2
-100 cycles	39.3	3.7
-125 cycles	56.2	6.8
-150 cycles	73.0	12.6
-175 cycles	91.0	16.1

cement concrete. The air content of hardened slag concrete was at the same level as in corresponding fresh concrete while normal concrete had lost about 1% of air. In spite of this the spacing factor of cement concrete was less than that of slag concrete.

The salt-scaling resistance of slag concrete was also better than that of portland cement concrete. This can be seen also in Figure 3. The losses of volume after 100 and 175 cycles salt-scaling test are merely 3.7% and 16.1% for slag concrete while the corresponding values for cement concrete are 39.7% and 91.0% respectively. Thus it seems that aged slag concrete is more salt-scaling resistant than corresponding cement concrete according to

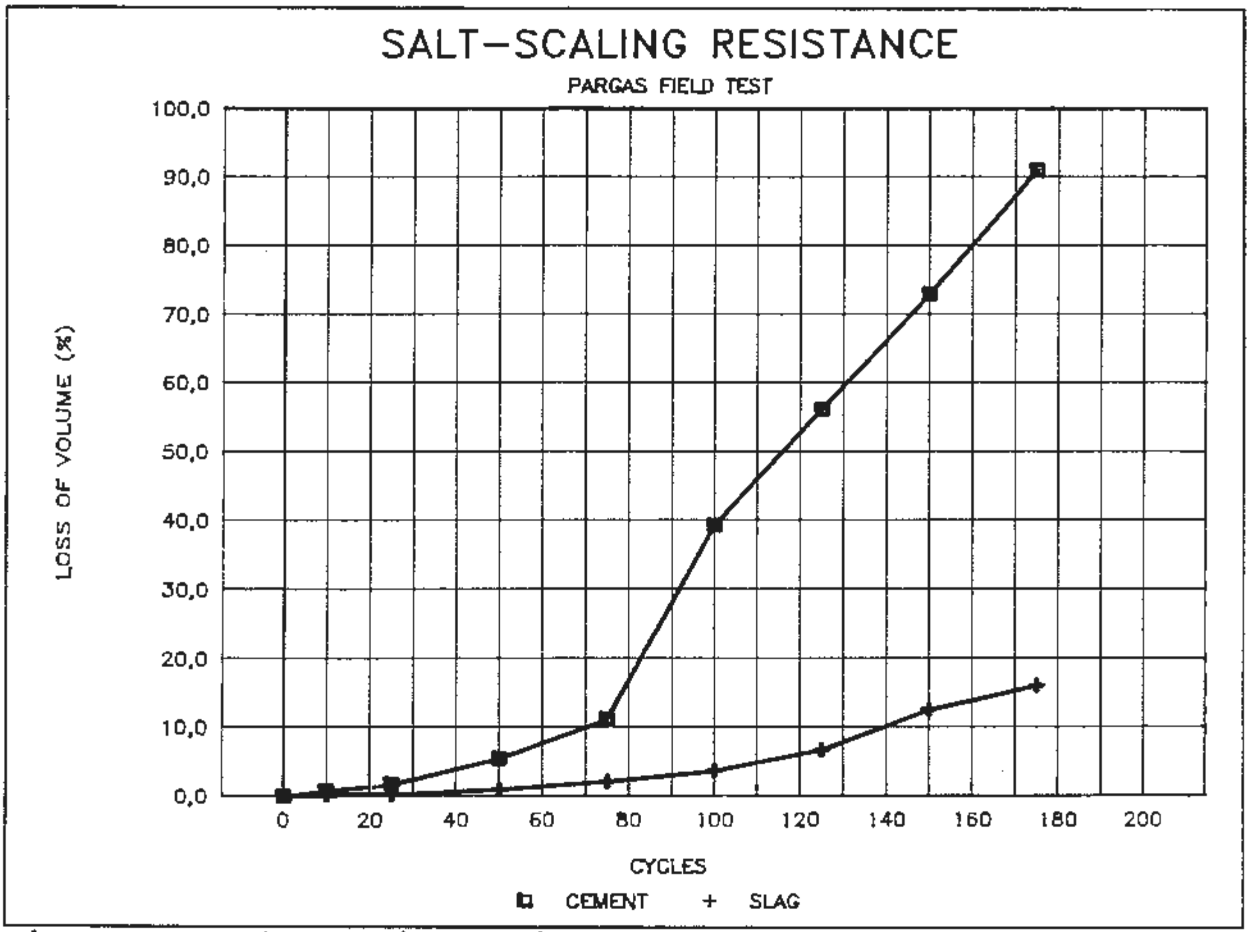

Figure 3. Salt-scaling resistance of a concrete road. Slag and cement concrete at Pargas after 6 years of outdoor exposure.

these tests carried out on cores taken from a road in south west Finland.

It could also be seen, that the scaling was most intensive on the cut surfaces of the test cylinders, while the upper (carbonated) surface remained nearly undamaged during 175 cycles. This indicates that the drilling of the cores can lead to microcracking of the specimen, which then leads to scaling.

3.3 Silica concrete

Silica has been used in edge beams of concrete bridges in Finland since 1983. The first edge beam with silica was cast at Kirkkojärvi-bridge on the Helsinki - Turku-highway on 30.11.1983. A larger amount of edge beams with silica were manufactured in the Pori Länsitie-project during 1984. In both of these cases the salt-scaling resistance of the cast concrete was studied. The mix designs and test results gained during casting these objects are shown in TABLE III.

TABLE III. Mix designs of edge beams of concrete bridges at Kirkkojärvi and Pori Länsitie (Karjaranta). Test results of concrete while cast.

	Bridge	
	Kirkkojärvi	Karjaranta
Mix proportions kg/m^3		
Cement	353	360
Silica	28	29
Water	144	170
Parmix L %-cem.	0.03	0.10
Melment L10 %-cem.	1.0	-
Parmix N %-cem.	-	2.0
Aggregate	1890	1755
Properties of fresh concrete		
Air content %		
- at ready-mixed plant	7.0	-
- at site	5.8	-
Slump mm	75	-
Properties of hardened concrete		
Compressive strength MPa		
- at 7 days	36.0	-
- at 28 days	47.5	48.6
Protective pore ratio %		
- minimum	-	26
- average	24	31
- maximum	-	38
Salt-scaling resistance Volume loss %		
- 10 cycles	0.0	0.2
- 25 cycles	0.3	0.5
- 50 cycles	-	1.5
- 75 cycles	-	3.7
-100 cycles	-	6.5

In summer 1989, cores with a diameter of 100 mm were drilled from the edge beams of Kirkkojärvi-bridge and Karjaranta-bridge at Pori. In the first bridge one of the edge beams was made with silica concrete and one with normal concrete. The proportioning and properties of normal concrete have not been available to the author. In Pori only silica concrete was used. The depth of carbonation, amount of water soluble chloride, compressive strength, capillary water absorption, optical analysis of air pore structure, analysis of microstructure and salt-scaling resistance of the concretes was studied. These results are given in TABLE IV. The salt-scaling resistance of Kirkkojärvi bridge edge beams could not be measured, because the bridge was widened and thus these edge beams were torn apart before the cores for this test were taken.

Analysis of the microstructure was made at the Concrete and Silicate Laboratory at the Technical Research Center of Finland (VTT) /4/. The analysis of normal concrete at Kirkkojärvi bridge showed the following results: concrete contained no silica, fly ash particles were noticed, concrete was air-entrained, crystals had gathered in pores to such an extent that parts of the smallest pores had been filled, very slight network type microcracking was observed in cement stone and depth of carbonation ranged between 150 - 1100 μm and was on an average 420 μm.

Analysis of the microstructure of silica concrete at Kirkkojärvi bridge showed the following: the specimen was silica concrete, concrete was air-entrained, pores were rather evenly distributed, but some larger bubbles existed, a slight amount of crystals had gathered into the pores, a crack, perpendicular to the surface, reached to a depth of about 5.5 mm from the surface, frost cracking reached to a depth of about 150 μm on the surface, slight network type cracking was observed in cement stone, mostly near the surface and the depth of carbonation ranged between 0 - 400 μm and on an average 100 μm, at the observed crack about 5.5 mm.

Analysis of the microstructure of silica concrete at Karjaranta bridge showed the following: the specimen was silica concrete, the concrete contained fly ash particles, a crack, perpendicular to the surface, reached to a depth of about 2.5 mm from the surface, the concrete was air-entrained, moderate network type cracking was observed in cement stone, mostly near the surface to a depth of about 5 mm and depth of carbonation ranged between 0 - 860 μm and on an average 250 μm, at the observed crack about 2.5 mm.

The depth of neutralization measured by means of fenolphatalen was greater than the depth of carbonation observed in microstructure analysis for silica concretes. The depth of neutralization was deeper in silica concrete at Pori, but less in silica concrete in

TABLE IV. Test results of edge beams of concrete bridges at Kirkkojärvi and Pori Länsitie (Karjaranta) after 5 years outdoor exposure.

	Bridge		
	Kirkkojärvi		Karjaranta
	Silica	Cement	Silica
Mix proportions kg/m^3			
Cement	353	?	360
Silica	28	?	29
Water	144	?	170
Parmix L %-cem.	0.03	?	0.10
Melment L10 %-cem.	1.0	?	-
Parmix N %-cem.	-	?	2.0
Aggregate	1890	?	1755
Properties of concrete after 5 years exposure			
Air content %	3.3	-	8.4
Spacing factor mm			
-Powers	0.20	-	0.17
-pores <800 μm	0.12	-	0.09
Compressive strength MPa	66.2	65.4	58.7
Chloride content %			
- 0-10 mm	0.26	0.13	0.02
- 25-35 mm	<0.01	0.01	<0.01
Capillary water absorption			
-Protective pore ratio %	27	30	40
-Total porosity l/m^3	175	196	198
-Coefficient of resistance to water absorption s/mm^2	13.23	80.42	17.68
-Capillarity factor kg/m^3	0.008	0.008	0.009
Salt-scaling resistance			6 / 5
Volume loss %			cores
- 10 cycles	-	-	-1.1/-1.1
- 25 cycles	-	-	0.6/ 0.5
- 50 cycles	-	-	1.9/ 1.5
- 75 cycles	-	-	19.0/ 2.7
-100 cycles	-	-	20.2/ 4.3
-125 cycles	-	-	26.0/ 6.0
-150 cycles	-	-	28.0/ 8.0
-175 cycles	-	-	30.7/10.7
-200 cycles	-	-	33.9/17.3

Kirkkojärvi than in normal concrete in the same bridge. Carbonation of normal concrete had reached deeper into the concrete than in silica concrete.

All the studied specimens contained network type microcracking. Microcracking was observed more in silica concrete. These cracks were thought to be formed due to the shrinkage of concrete.

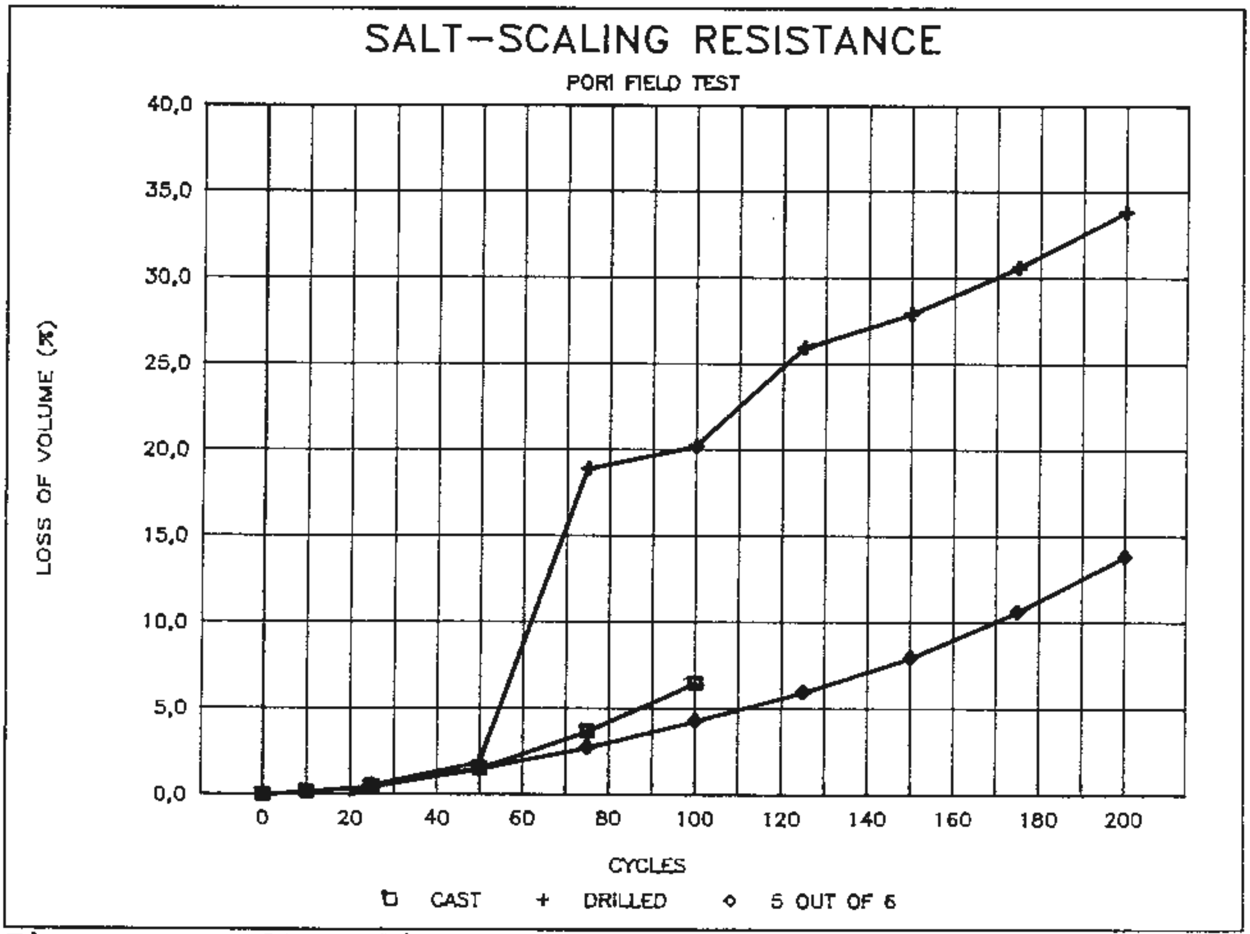

Figure 4. Salt-scaling resistance of edge beams in Karjaranta bridge on Länsitie at Pori. Cast denotes cubes cast and tested in 1984, drilled denotes the cores tested in 1989 and 5 out of 6 denotes the drilled cores excluding no 5.

The salt-scaling resistance of edge beams in Karjaranta bridge at Pori after 5 years outdoor exposure is compared with the tests made with cast test specimens 100*100*100 mm^3 in size made during casting the Länsitie bridges. This comparison is shown in Figure 4. From this figure we can see that the salt-scaling resistance of silica concrete is as good after 5 years outdoor exposure as it was originally without any ageing treatment. However, one of the drilled cores disintegrated totally between 50 and 75 cycles. No clear reasons for this behavior could be found. This result indicates that all the concrete in these edge beams is not homogenous, but can contain places of weakness or lack of frost-resistance. One possible reason is that the edge beams were cast with a pump simultaneously with the deck of the bridge, which was cast with non-air-entrained concrete.

It could be seen, that the scaling was most intensive on the cut surfaces of the test specimens, while the upper surface was nearly undamaged after 200 cycles. This gives reason to believe that the drilling of the cores leads to microcracking near the cut surface, which then leads to scaling during the test. The aged upper surface did not suffer during 200 cycles of salt-scaling test indicating that ageing is not a problem for this kind of silica concrete. Thus, it can be concluded that outdoor exposure does not decrease the salt-scaling resistance of silica concrete to any great extent.

3.4 Discussion and conclusions

These field tests have been made using normal casting procedures, without any extra quality control or extra care in manufacturing. The concretes have been mixed at normal ready-mixed concrete plants, cast according to standard systems, cured with normal methods and aged under normal outdoor exposure.

The results obtained here indicate that silica concrete can be more vulnerable to microcracking than normal concrete, but the reason for this could be the drilling of the cores. When concrete cores are drilled from the structure, drilling can cause microcracking to the surfaces of the specimen and the further manufacturing of a thin slice for microscopic analysis can increase this cracking. Also, during salt-scaling tests the scaling becomes more intensive on these cut surfaces. Thus, it is very dangerous to draw final conclusions based only on microscopic analysis of small thin slices of concrete. One other possible reason for the microcracking of silica concrete could be the larger plastic shrinkage of silica concrete.

The salt-scaling resistance of slag concrete was found to be better after 7 years of outdoor exposure than that of normal concrete. Also, the silica concrete did not suffer any lack of salt-scaling resistance after 5 years outdoor exposure. However, one of the six drilled test specimens of silica concrete disintegrated during the test, indicating at least local lack of salt-scaling resistance.

The results show that the ageing in outdoor conditions in Finland is not so harmful to concrete containing additions, as has been claimed by laboratory testing of artificially aged concrete.

4 CONCLUSIONS

In this study, the frost-resistance of concrete containing additions has been investigated based on field tests and previously reported laboratory tests. The results can be summarized as follows.

Addition of silica increases the frost-resistance of concrete. This influence is larger than the influence of silica addition on the strength of concrete. However, high strength silica concrete also has to be air-entrained to ensure good frost-resistance in practice.

Frost-resistance of concrete is not affected by the use of slag or fly ash, when the air content and strength of concrete are kept constant.

Air content of concrete is the most important factor influencing the frost-resistance of concrete. However, an optimal air content can be found, above which an increase in the amount of air results in an decrease in frost-resistance. This optimal air content seems to decrease when the strength of concrete increases, or silica fume is added to the concrete. Thus, also strength and impermeability of concrete have significant effects on the frost-resistance of concrete.

Different testing methods for frost-resistance of concrete give differing results for different concretes. This is probably also one reason why differing opinions of the influence of additions on the frost-resistance of concrete can be found in previous studies. A more profound knowledge of the mechanism of frost attack is still needed to be able to construct a reliable test for the frost-resistance of concrete in actual practice.

All additions increase the dosage requirement of an air-entraining agent to give a certain amount of air. In the case of silica this is more closely related to the functioning of the plasticizing agent needed in silica concrete than silica itself.

The stability of air-entrainment is better with silica concrete than with normal, slag or fly ash concrete. The loss of air increases relative to the increasing amount of originally entrained air. The air pore structure is not influenced by the use of additions, when the air content is kept constant.

Problems with the frost-resistance of concrete have been encountered when excessive amounts of additions have been used in laboratory tests. Thus, we should limit the allowed amounts of ground granulated blast-furnace slag, pulverized coal fly ash and silica in frost-resistant concrete to 50%, 25% and 10% by weight of total binder content, respectively.

The ageing of concrete containing additions, can alter the behavior of concrete under freeze-thaw conditions. The tests made in actual outdoor exposure over a 5 to 7 year period, indicate that this is not as big a problem as has been claimed, according to laboratory tests made with artificially aged concretes. However, this matter needs to be studied in still more detail and with longer periods of exposure on actual structures.

REFERENCES

/1/ Virtanen, J., Mineral By-Products and Freeze-Thaw Resistance of Concrete. In: Nordic Concrete Research. Oslo 1984. The Nordic Concrete Federation. Publication No. 3. p. 191-208.

/2/ Virtanen, J., Effects of mineral by-products on the frost-resistance of concrete. Otaniemi 1990. Helsinki University of Technology, Department of Structural Engineering. Report 107. 108 p.

/3/ Tutkimusselostus N:o BET91487. Espoo 1989, Valtion Teknillinen Tutkimuskeskus, Betoni- ja silikaattitekniikan laboratorio, 2 p.

/4/ Tutkimusselostus N:o 188/0/88/BET. Espoo 1988, Valtion Teknillinen Tutkimuskeskus, Betoni- ja silikaattitekniikan laboratorio, 7 p.