

FROST/SALT SCALING TESTING OF CONCRETE - IMPORTANCE OF ABSORPTION DURING TEST



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ABSTRACT

This paper presents a review of previously published data on frost/salt scaling and absorption in the concrete during freeze/thaw test. The data show that there is a good correlation between scaling and absorption during test, that freezing and thawing leads to an increased absorption compared to isothermal water suction and that the presence of NaCl leads to higher absorption than pure water during freeze/thaw. Results of some new laboratory tests on scaling of concrete by two different test methods (SS 13 72 44 - "The Borås method" and the CDF - test) with water and 3 % NaCl - solution are presented and discussed. In addition to scaling, the absorption during test was measured, and ultrasonic pulse velocity (UPV) was measured as an indicator of possible internal cracking. (Normally internal cracking is measured by resonant frequency). The absorption measurements are used to explain part of the very large increase in deterioration normally observed both in field and in laboratory when a concrete surface is exposed to salt solution instead of water during freezing. The concretes tested are from a large European cooperative test conducted by CEN TC 51/WG 12/TG 4 and Forschungsinstitut der Zementindustrie, Düsseldorf, during the spring of 1993 and known as The Second European Round Robin Test. Scaling, UPV and absorption were measured on both sawn and moulded surfaces for the specimens tested according to SS 13 72 44 and moulded surfaces for the specimens tested according to the CDF - test. The results of frost/salt scaling and absorption measurements of the same concrete quality tested with pure water and 3 % NaCl confirm that the presence of NaCl results in both higher damage and higher absorption compared to tests with pure water for both test methods. Calculations of increase of saturation in the top layer of the specimens illustrate this. The results thus seem to confirm earlier findings; that the presence of NaCl during freezing leads to higher degree of saturation than pure water.

Key words: Concrete, durability, frost/salt scaling, test methods, round robin test, absorption, degree of saturation

1. INTRODUCTION - SCOPE OF INVESTIGATION

Normally in frost/salt scaling tests the surface to be tested is exposed to water or salt solution before start of freezing and thawing (usually 3 - 7 days). This leads to a higher degree of saturation in the surface zone of the specimen before start of test. The mechanisms involved in the transport of water/salt solution, freezing, the increase in pressure and finally the disruption of the concrete is discussed briefly in sections 2 and 6. In early work relevant to frost damage in presence of de-icing salts (Verbeck and Klieger /1/ and Powers /2/) osmotic pressure was postulated as a major cause of deterioration. Increased degree of saturation due to deicing salts has been proposed by Fagerlund /3/ as a contributing cause of disruption. A comprehensive review on frost/salt scaling mechanisms has recently been made by Marchand et al /4/. In the present paper some previous experimental data on frost/salt scaling and absorption during freeze/thaw are discussed. Then results with two different frost/salt test methods are presented and the large increase in scaling observed in the presence of deicing salts compared to pure water are related to differences in absorption.

2. BACKGROUND AND SOME PREVIOUS INVESTIGATIONS

The importance of the degree of saturation for frost deterioration has been known for a long time, e.g. Fagerlund /3, 5/. To be able to give an accurate value of the degree of saturation for a given concrete, the freeze/thaw test should be performed in a sealed condition as described in the test procedure given in /6/. In /6/ the concrete specimens are preconditioned to different degrees of saturation and the damage measured as reduction in dynamic modulus, here referred to as internal cracking or volume deterioration. (Deterioration due to internal cracking is probably related to other mechanisms of deterioration than those responsible for scaling since internal cracking has been observed in several high strength concretes (HSC) where practically no scaling was observed /13/). However for an "open test" /7/ e.g. a test where the concrete can take up water or salt solution during freezing and thawing cycles (such as a frost/salt scaling test) the degree of saturation will probably vary within the specimen due to the transport of moisture from the surface to the interior of the specimen. An uneven distribution of moisture will exist in most concretes during the test unless a state of saturation is obtained at the start. The existence of moisture gradients in the specimen will depend on the curing conditions of the concrete and the concrete composition:

- If the concrete specimen is cured in water before start of the test the moisture state of the interior will depend on the ability of water to be transported in the concrete, eg. w/c, degree of hydration, type of cement, use of additional cementing materials and self-desiccation. The outer parts will have a higher degree of saturation in this case.
- If the concrete is cured in air the moisture distribution will depend on the RH of the air compared to the RH of the pore system of the concrete and concrete composition.
- If the concrete is cured in a sealed condition a uniform moisture distribution should theoretically exist in the specimen. The moisture content will depend on the concrete composition (self desiccation) and degree of hydration.
- If the concrete has been exposed to any other type of curing, for example involving cyclic wetting and drying the moisture state will depend on the specific climate history.

Fagerlund /8/ investigated the effect of different salt concentrations on frost deterioration. 9 mortars with w/c = 0.40, 0.60 and 0.70 with 3, 6 and 8 % nominal air void content were investigated. Two different curing methods were used: 1) in water for 6 weeks and in air for 2 weeks, and 2) in water for 6 weeks, air dried for one week and then again water stored for two weeks. Measurements were made of:

- degree of saturation after 13 days storage in pure water and 2.5 %, 5 % and 10 % NaCl solutions
- scaling and degree of saturation after 12 freeze thaw cycles
- difference in degree of saturation between 12 cycles of freeze/thaw and 13 days submerged
- length change during freezing.

The results showed that absorption was higher during freeze/thaw than during submersion at constant temperature, and the absorption was higher when freeze/thaw took place in salt solution than that in water. For all air dried concretes the scaling was largest for 2.5 % NaCl solution on the outside. The results varied for water stored specimens, but in all cases salt solution on the outside resulted in higher scaling than pure water. The length change measurements showed very little expansion when the degree of saturation was low, and large expansions for specimens with high degree of saturation. Highest expansion during freezing was measured for specimens stored in a 2.5 % NaCl solution. The differences in degree of saturation (ΔS) reached after 12 cycles of freeze/thaw are shown in figure 1. From the figures it is clear that the degree of saturation increases with freezing in the presence of NaCl and there is a tendency that 2.5 - 5 % concentration results in the highest increase in degree of saturation. Note that ΔS is related to the whole specimen volume. If there are moisture gradients in the specimens the local degree of saturation at the surface layer will be even larger.

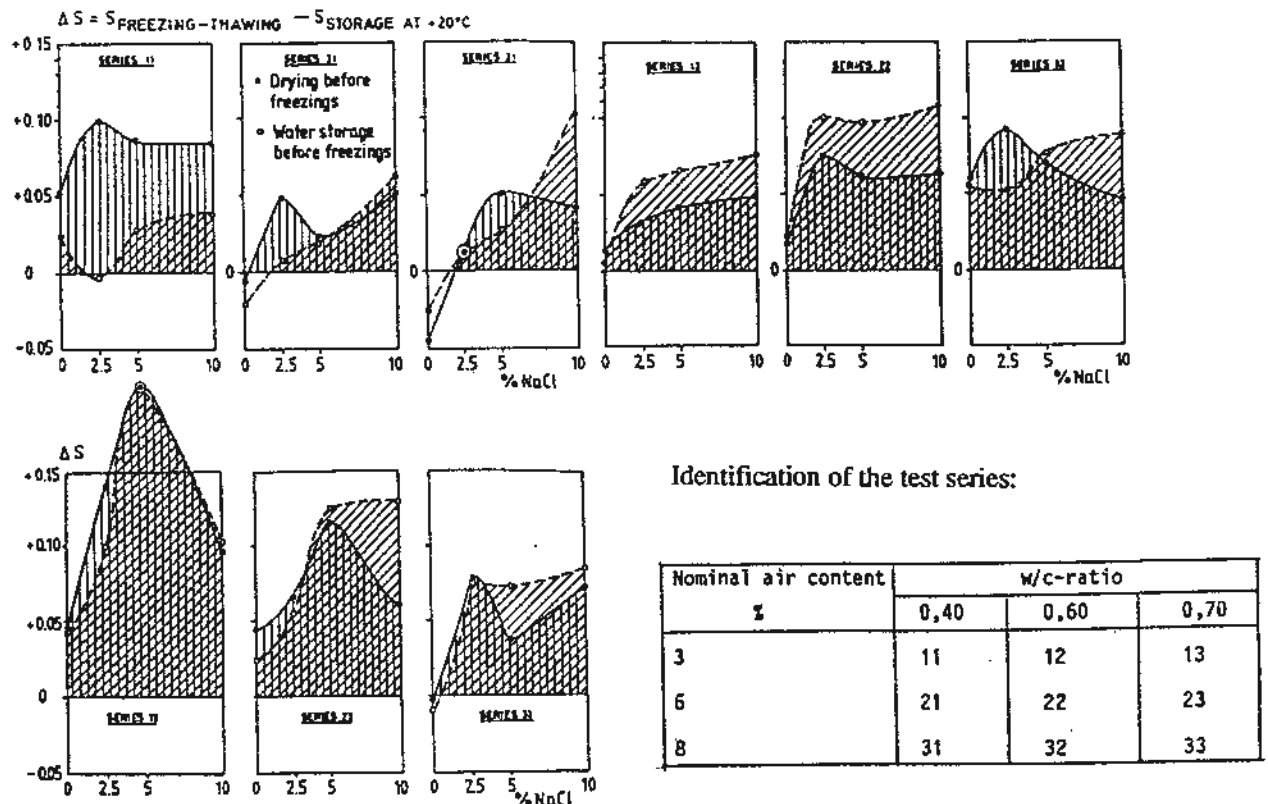


Figure 1: The difference in degree of saturation reached after 12 cycles of freeze/thaw and after 13 days of isothermal absorption, from Fagerlund /8/.

The degree of saturation of specimens submerged but not freeze/thaw tested (figure 1) was only tested on initially air dried specimens, whereas freeze/thaw testing was performed after both curing methods.

MacInnis and Whiting /9/ measured the amount of water retained in concrete initially saturated with different salt concentrations and then dried at different relative humidities. They found that concrete with salt solution had higher degree of saturation than concrete with pure water after drying at a given RH. This is of course expected since in a salt solution the water has a lower chemical potential (lower RH) and consequently will evaporate at lower RH. The result demonstrates one reason for increased deterioration in field concrete in the presence of salts - namely a higher degree of saturation. The argument is not valid for laboratory testing directly - since in laboratory tests the concrete surface is continuously covered with a salt solution. Subsequent expansion measurements during freeze/thaw /9/ showed largest expansion for concretes with salt solution.

Measurements of absorption during frost/salt scaling testing is a very simple method of assessing the increase in the degree of saturation in a specimen during freeze/thaw testing. Sellevold et al /10/ performed simultaneous measurements of weight and scaling according to SS 13 72 44 /11/ (see section 4.1) on six different concretes. In figure 2 the results for absorption during test are shown.

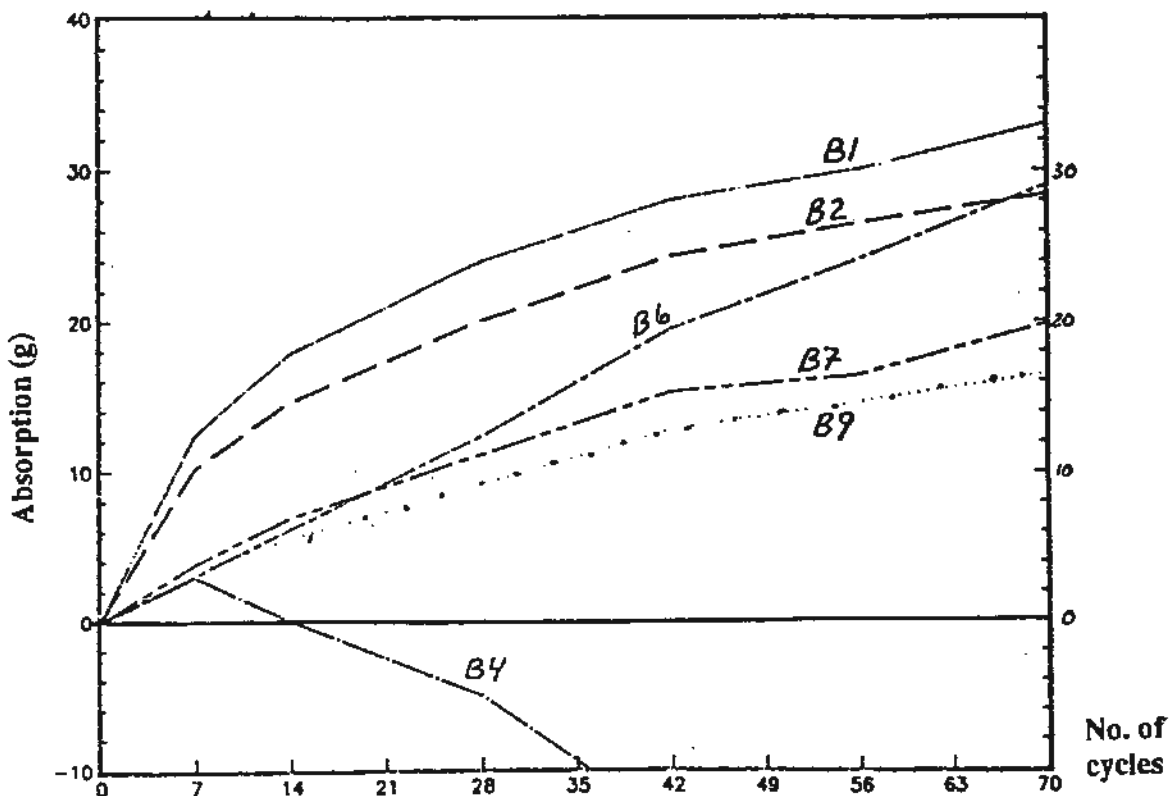


Figure 2: Simultaneous measurements of absorption and scaling for six different concretes during the SS 13 72 44 frost/salt scaling test, from Sellevold /10/ (Measurements performed by Norcem).

All concretes were cured in water for 14 days, then isolated for approximately 3 months, sawn and tested according to SS 13 72 44 (11 days 50 % RH/20 °C, 3 days pure water on test surface and then start of freezing and thawing with 3 % NaCl on the surface). One of the concretes, B4, had undergone a drying/resaturation pretreatment before start of test. This is known to result in very high scaling, see Sellevold et al in /12/. When measuring absorption in the specimens of concrete B4, it is seen from figure 2 that the very high scaling (17.7 kg/m² after 56 cycles) resulted in an apparent weight loss due to loss of evaporable water (w_e) in the scaled - off concrete. It is therefore not possible to measure the relative increase in saturation for this concrete. For the other 5 concretes the amount of scaled - off material is much lower, and consequently also the loss of w_e in the scaled - off concrete. Whether an apparent loss in total mass will occur will depend on amount of scaled off concrete, absorption in the specimen and w_e of the concrete. w_e for the concrete depends on w/c, amount of cement and degree of hydration. The total air contents of the concretes were measured by the PF- method. In figure 3 absorption is plotted vs. scaling after 56 cycles.

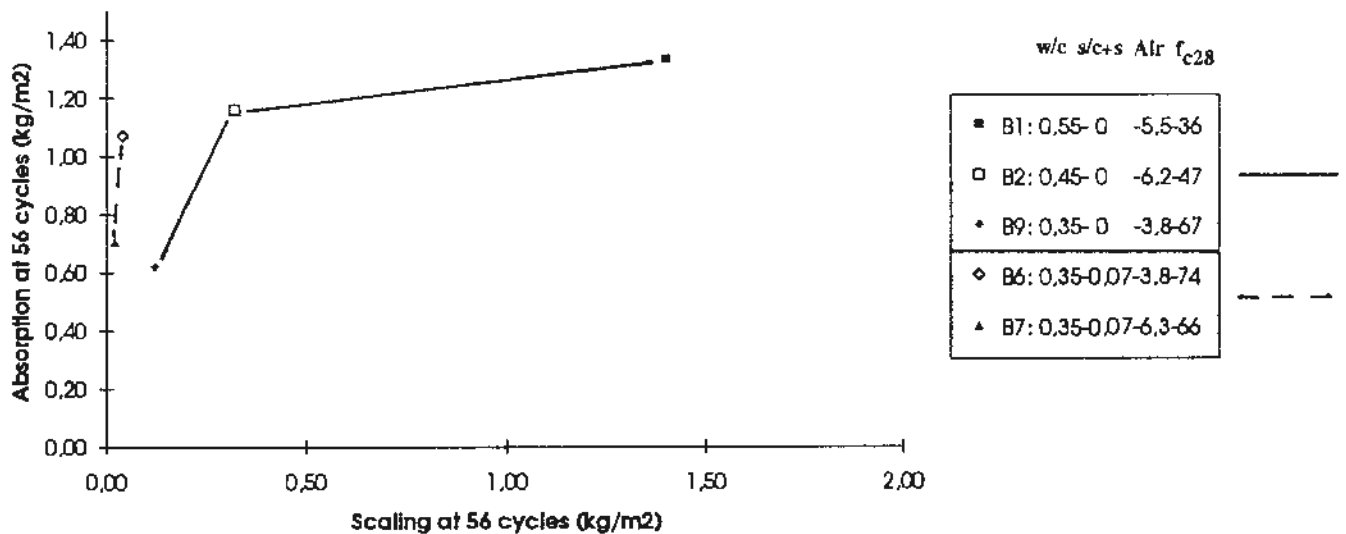


Figure 3: Scaling and absorption during freeze/thaw testing of concrete, data from Sellevold et. al /10/.

Figure 3 shows a good relationship between scaling and absorption during test. The scaling of the concretes without silica fume (0.35, 0.45 and 0.55) can be ranged according to their water uptake during the test; both scaling and absorption is lowest for the w/c = 0.35 concrete and highest for the w/c = 0.55 concrete. For B1 and B2 the total air content (which of course has a large influence on the results) were on the same level, but for B9 the air content is lower. For the two concretes with silica fume the scaling is on a lower level for a given amount of water uptake compared to the w/c = 0.35 concrete without silica fume. The difference in scaling between the two silica fume concretes of equal w/c and silica fume content corresponds to their differences in airvoid content and absorption during test: reduced scaling by increased airvoid content and reduced water uptake during test. The positive effect of silica fume on frost/salt scaling is in accordance with other experiences /12, 13, 14/ and correlates with the reduced amount of ice formation normally observed for the temperature range of the frost/salt test /12, 15/. In the investigation /10/ 15 mm slices

from the top of the test specimens were cut after 78 cycles of freeze/thaw testing to measure their degree of saturation. For the $w/c = 0.45$ and 0.55 concretes the degree of saturation corresponded to water filling of approximately 1 % air voids. For the more dense concrete with $w/c = 0.35$ and 7 % silica fume no air voids were filled.

In an investigation by Bordeleau, Pigeon and Banthia /16/ on the effect of latex modification on frost/salt scaling of concrete the results showed that the addition of latex both reduced absorption during test and amount of scaling. In figure 4 data from /16/ are plotted as scaling vs. absorption after 50 cycles.

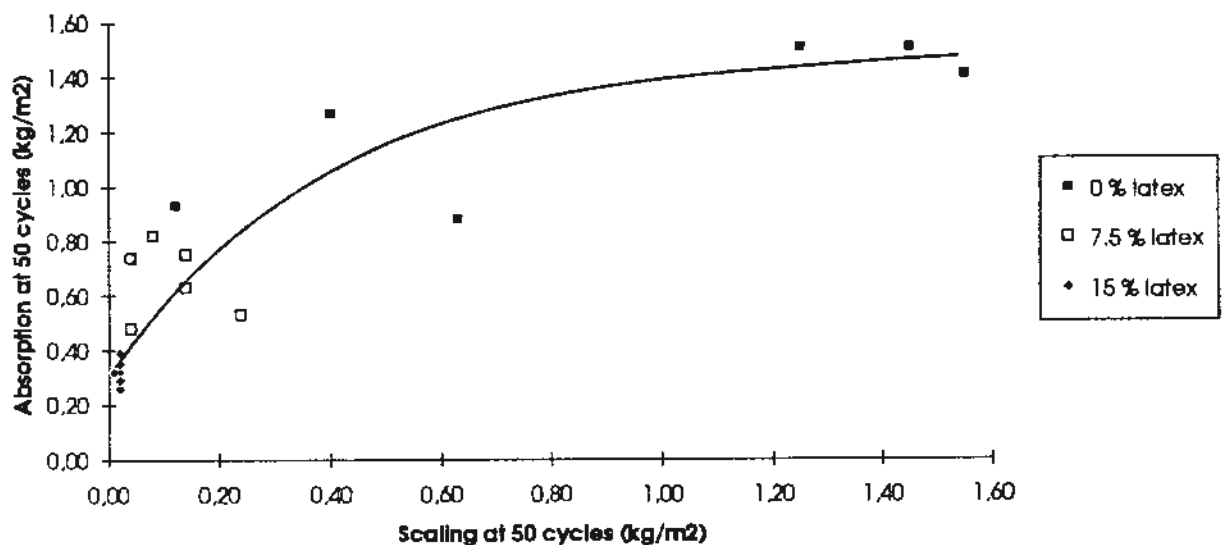


Figure 4: Frost/salt scaling vs. absorption during test, 50 cycles of freezing and thawing according to ASTM C 672, $w/c = 0.30 - 0.35 - 0.40$, Air content = 2.6 - 15.2 % $f_{c28} = 33.5 - 58.4$ MPa, data from Bordeleau, Pigeon & Banthia /16/.

The concretes were cured 24 hours at 100 % RH, 4 weeks at 50 % RH and 23 °C. The reference concretes (without latex) were stored for additional 2 days at 100 % RH and 4 weeks at 50 % RH and 23 °C before start of test. All test surfaces (moulded) were covered with pure water 3 days before start of freezing and thawing with 2.5 % NaCl solution at 1 cycle per day except on weekends during which the specimens were kept frozen. Absorption during test was calculated by adding scaled - off concrete to the weight of the specimen. Internal cracking was observed on some of the specimens, and in one series the two parallel specimens had large scatter (rating 0 and 2 according to ASTM C 672) . These specimens are not used in the plot. For each level of latex (0, 7.5 and 15 %) three different w/c (0.30, 0.35 and 0.40) were tested. For each w/c - ratio concretes with low, medium and high air void spacing factors were tested. The w/c and air void content of course will influence the frost/salt scaling durability of the concretes. Figure 4 (like figure 3) shows a good relationship between scaling and absorption for the different concrete compositions. The very good performance of concrete with latex (styrene butadiene) in the frost/salt scaling test was attributed to the formation of a continuous film within the hydrate products that hindered penetration of water and chloride ions. (Latex will influence on other properties of hardened concrete, but here we have focused on absorption and scaling).

In a recent report by Lindmark /17/ an investigation on the effects of different salt concentrations on scaling, internal cracking and absorption of concrete tested in the Borås test were performed. All 9 combinations of 0, 3 and 6 % NaCl concentration on the surface and in the pore system were tested at 5 different types of freeze/thaw cycles on one concrete quality (making a total of 45 test series). The results showed highest scaling for 3 % outer salt concentration whereas the inner salt concentration seemed to play a less important role. The results from the measurements of absorption (performed on 4 of the 5 different types of freeze/thaw cycles) showed that for one of these 4 freeze/thaw cycles all 9 combinations of salt concentrations had a substantial mass loss. For the other 3 freeze thaw cycles the absorption was higher for the 8 combinations tested with salt than for the one combination tested with pure water.

The conclusion of this limited literature survey is that salt solution gives more absorption than water, and that scaling in general seems to be related to absorption during test.

3. CONCRETE MIXES TESTED

The concretes tested were specimens from a large European round robin test, /18/. In /18/ results from all 17 participating laboratories are given. In table 1 the concrete mixes and test methods used are given.

Table 1: Concrete mixes tested according to SS 13 72 44 and the CDF - test. For the CDF - test moulded surfaces were tested, and for SS 13 72 44 both moulded and sawn surfaces were tested.

Mix no.	Composition	Test conditions
1	Cement: 350 kg/m ³ w/c = 0.45 air content 5 - 6 %	3 % NaCl
2A	Cement: 350 kg/m ³ w/c = 0.45	
2B	no air entrainment	Pure water
3	Cement: 280 kg/m ³ w/c = 0.65 no air entrainment	

As seen in table 1 the denotation "Mix" refers to both concrete mix and test condition: 3 % NaCl or pure water. The concrete specimens were moulded in Germany by VDZ and sent to the participants of the round robin test by plane in specially designed wooden boxes. In tables 2 and 3 data about the concretes are given. More details about the concretes and results from the 2nd European Round Robin Test are given in reference /18/.

Table 2: Age of concrete specimens (15 cm cubes): casting, transport and testing

Test series	Received, sawn, stored at 65 % RH, 20 °C	Taken out of 65% RH, 20°C, start presuction: - water (SS) - 3% NaCl (CDF)	Start freeze/thaw testing
	Age (days)	Age (days)	Age (days)
Mix 1 - SS	16	29	32
Mix 1 - CDF	16	29	36
Mix 2A - SS	17	28	31
Mix 2A - CDF	17	28	35
Mix 2B - SS	17	29	32
Mix 2B - CDF	10	28	35
Mix 3 - SS	15	27	30
Mix 3 - CDF	10	28	35

It is assumed that the moisture conditions of the test surfaces were rather equal for the three w/c = 0.45 mixes (Mix 1, 2A and 2B) after the storage at 65 % RH and 20 °C.

Table 3: Properties of fresh and hardened concrete, data from /18/

Mix No.	Fresh concrete Air content (%)	Hardened concrete, (28 days) Compressive strength, (N/mm ²) ¹⁾
1	5.1	46.6
2A	2.2	60.8
2B	2.2	60.4
3	2.2	38.3

- 1) Cubes 15 by 15 by 15 cm
- 2) Degree of compactibility according to DIN 1048
- 3) Flow diameter according to DIN 1048

4. TEST PROGRAMME AND TEST METHODS

The concrete mixes were tested according to two different frost/salt scaling test methods. For each test method and concrete mix the following measurements were performed:

- weight of scaled off mass
- weight of test specimen after scaled off concrete has been removed
- ultrasonic pulse velocity parallel to the test surface to measure possible internal cracking in the specimens

Specimens for frost/salt testing were sawn from the cubes at arrival (see table 2) as 50 by 150 by 150 mm slabs. For the CDF test moulded surfaces were tested, and for SS 13 72 44 both moulded and sawn surfaces were tested.

4.1 Swedish Standard SS 13 72 44, /11/

The test method specifies a normal air cooled cabinet and can be run in most types of climatic chambers with abilities to control the temperature between + 20 and - 20 °C. For each Mix both sawn and moulded surfaces were tested. The sawn surface specimens were taken parallel to, and always 50 mm from the twin moulded surface specimen. During storage at 65 % RH and 20 °C (note that 65 % RH was used in this round robin test instead of the standardized 50 % RH) the specimens were prepared according to the standard. A 1 mm thick non - absorptive rubber was used. The 50 mm high sides of the slabs were sealed with epoxy paint before the rubber cloth was glued to the specimens to ensure that absorption and scaling would occur only on the top surface of the specimens. A polyamid amine epoxy paint was used for this purpose. Ultrasonic pulse velocity was measured directly on the rubber cloth without transmission gel by a PUNDIT MK V, 54 MHz. Figure 5 shows preparation of test specimens and temperature in the salt solution during one freeze/thaw cycle. Thermocouples were placed in the salt solution of specimens at the top, middle and bottom of the freeze/thaw cabinets to check that the temperature was within the specified limits of the standard. Four parallel specimens were used and the specimens were rotated randomly in the cabinets between each measurement. Leakage of salt solution between rubber and concrete during test was observed on 7 of 32 specimens from 42 to 56 cycles, and these scaling values were not accounted for in the results. The scaled off material was brushed off, dried at 105 °C for 24 hours and weighed with a balance of 0.01 g accuracy. In the results scaling is calculated and rounded off to the nearest 0.01 kg/m².

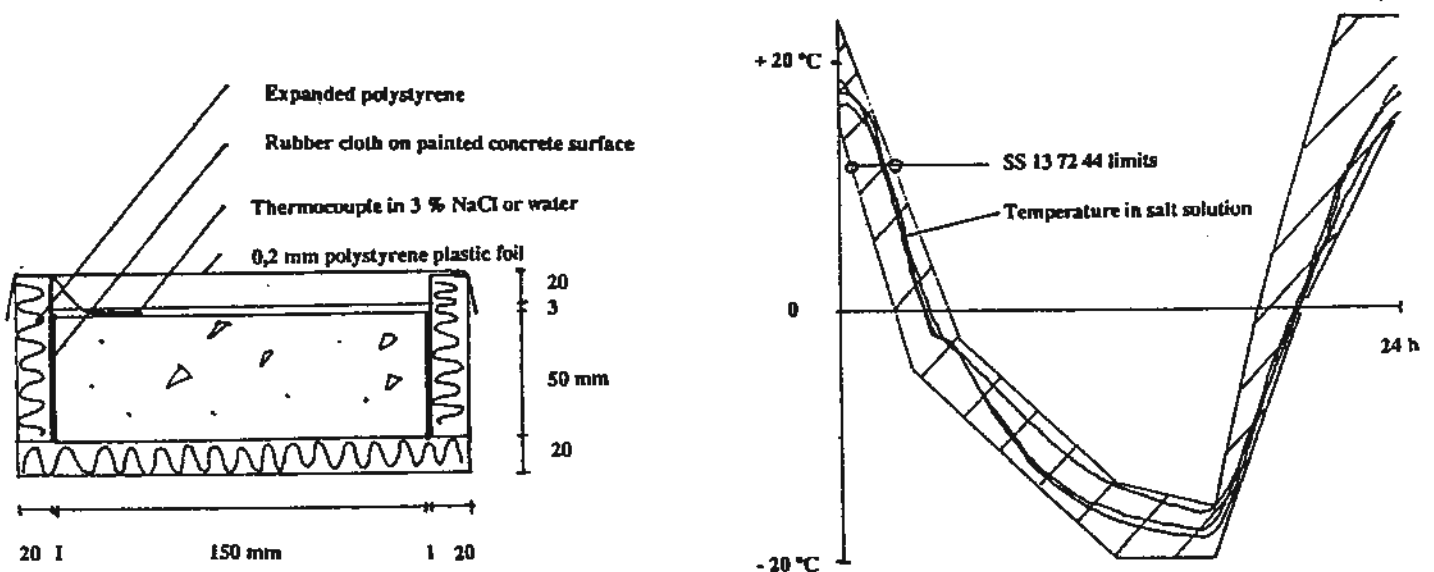


Figure 5: Preparation of test specimens and temperature cycle for SS 13 72 44, /11/

4.2 CDF - test, /19/

The method specifies a specially designed equipment with a cooling bath (glycol) in which the temperature is regulated very accurately. Due to the good heat exchange between the cooling bath and the containers with test specimens a very good control with the temperature in the NaCl - solution is obtained according to /19/. Another difference between the CDF - test and SS 13 72 44 is that presuction before start of freezing and thawing is performed with 3 % NaCl (7 days) in the CDF - test, whereas pure water (3 days) is used for presuction in SS 13 72 44. In this test three parallel samples were used instead of five due to equipment size limitations, and each specimen was 50 mm thick (as in SS 13 72 44). A polyamid amine epoxy paint was used to seal the sides of the specimens. Ultrasonic pulse velocity was measured directly on the painted surface of the concrete. A water based transmission gel was used. Insulation was put on the unpainted top surface of the specimen to prevent condensation of water during thawing and thus absorption occurred only on the surface exposed to scaling. In figure 6 test setup and freeze thaw cycle is shown. The temperature in the salt solution at the concrete surface was measured in three of the six containers that were run simultaneously. The temperature was always kept within the range of the test specification. Measurements and calculations of scaling were performed in the same way as for the SS 13 72 44 specimens.

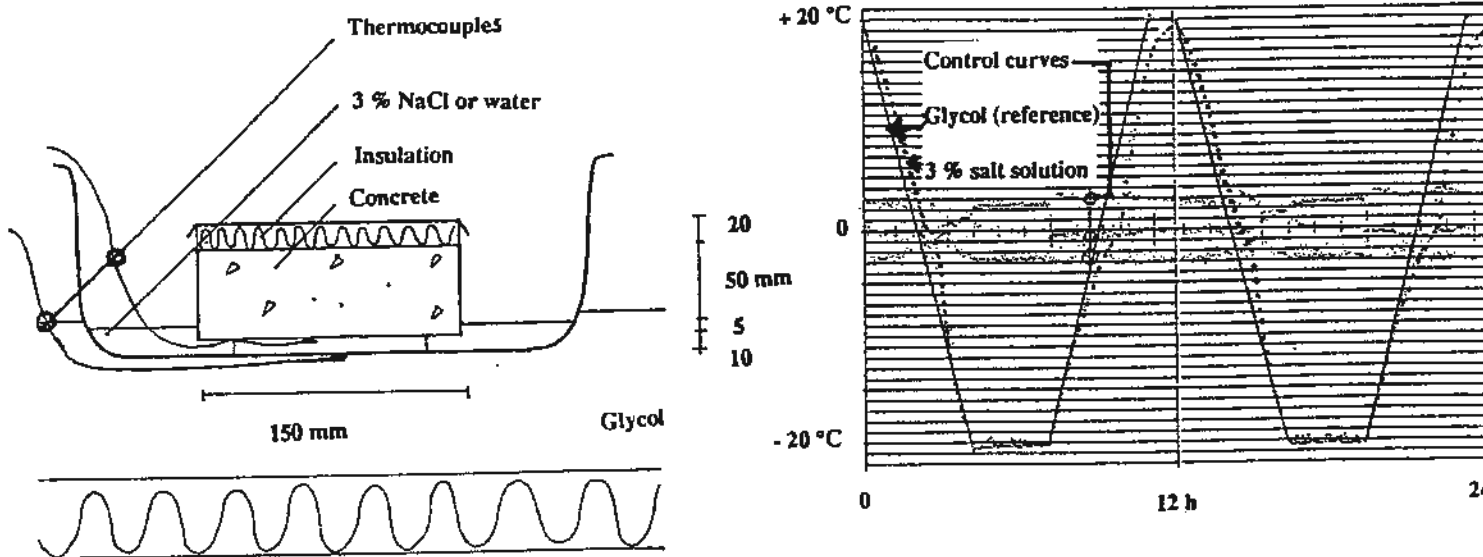


Figure 6: Test setup and freeze/thaw cycle for the CDF - test, /19/

4.3 Porosity and method to compensate loss of evaporable water in scaled off concrete. Measurements of absorption during test

Air content of hardened concrete was measured according to the PF-method /20/ on the same types of slabs as tested for frost/salt scaling. Specimens were taken next to frost/salt specimens. The testing procedure consists of measuring the weight of the concrete specimen in different moisture conditions, measuring the volume and then calculate porosities and densities:

m_{dry} :	specimen mass dried to constant weight (105 °C)
$m_{suction}$:	specimen mass after immersion in water ("capillary porosity")
$m_{pressure}$:	specimen mass pressure saturated (10 MPa water pressure)
V :	volume measured by weighing in water

The following porosities are calculated:

$\epsilon_{suction}$	(suction porosity)	$= (m_{suction} - m_{dry}) / V$	(vol-%)
ϵ_{macro}	(macroporosity, air content)	$= (m_{pressure} - m_{suction}) / V$	(vol-%)
PF	(Pore protection Factor)	$= \epsilon_{macro} / (\epsilon_{macro} + \epsilon_{suction})$	(%)

The suction porosity determined this way is a function of the volume fraction of cement paste, the w/c - ratio and the degree of hydration, assuming that no water is absorbed by the aggregate. The air content is represented by pores that are not filled by capillary suction after immersion in water, but are filled at subsequent application of 10 MPa water pressure. In addition different densities can be calculated from the data (dry density, solid density). Sellevold /20/ has shown that air content measured with the PF-method and air content measured optically on plane sections correlate very well. In addition the data from the PF - test were used to estimate the loss of w_e in the scaled - off concrete (which is dried at 105 °C in standardized testing). The mass of the scaled off concrete is multiplied with the ratio $m_{suction} / m_{dry}$ to compensate the loss of w_e (evaporable watercontent) in the scaled-off concrete. The content of NaCl in the concrete is not taken into account. Measurements of absorption during test was performed by weighing the surface dry frost/salt specimen after removal of the scaled off mass.

5. RESULTS

Table 4 shows scaling (kg/m^2), table 5 shows absorption (kg/m^2), table 6 shows ultrasonic pulse velocities (m/s) and table 7 shows porosities and other results from the PF-method. In /18/ results from all 17 participating laboratories are given.

Table 4: Scaling (kg/m^2)

Test series - Mix	No. of cycles		
	28	56	250
SS sawn surfaces			
Mix 1	0.11	0.14 1)	-
Mix 2A	3.17	7.14 2)	-
Mix 2B	0.05	0.07	-
Mix 3	0.02	0.03	-
SS mould surfaces			
Mix 1	0.08	0.09	-
Mix 2A	6.71	11.13 2)	-
Mix 2B	0.04	0.06	0.18 3)
Mix 3	0.11	0.30 2)	-
CDF mould surfaces			
Mix 1	0.17	0.36	-
Mix 2A	1.91	5.78	-
Mix 2B	0.04	0.07	-
Mix 3	0.12	0.59	-

- 1) Leakage one specimen 42 - 56 cycles 2) leakage 2 specimens 42 - 56 cycles
3) Measurements at 140, 189 and 250 cycles (no leakage of water)

Table 5: Absorption (kg/m^2)

Test series - Mix	pre-suction	No. of cycles			
		0	28	56	250
SS sawn surfaces	1)				
Mix 1	0.43	0	0.80	1.14	-
Mix 2A	0.43	0	0.90	1.47	-
Mix 2B	0.46	0	0.57	0.88	-
Mix 3	0.98	0	1.06	1.29	-
SS mould surfaces	1)				
Mix 1	0.62	0	0.75	1.11	-
Mix 2A	0.54	0	0.75	1.17	-
Mix 2B	0.62	0	0.61	1.03	1.38
Mix 3	1.43	0	1.19	1.28	-
CDF mould surfaces	2)				
Mix 1	0.91	0	0.30	0.50	-
Mix 2A	0.80	0	0.64	0.94	-
Mix 2B	0.92	0	0.46	1.08	-
Mix 3	2.03	0	0.99	1.78	-

1) 3 days pure water 2) 7 days 3 % NaCl

Table 6: Ultrasonic Pulse Velocity (m/s)

Test series - Mix	No. of cycles			
	0	28	56	250
SS sawn surfaces				
Mix 1	3692	3775	3888	-
Mix 2A	3970	3907	3728	-
Mix 2B	3781	3834	3743	-
Mix 3	3678	3823	3754	-
SS mould surfaces				
Mix 1	3787	3881	4049	-
Mix 2A	3918	3633	3764	-
Mix 2B	3847	3996	3988	4481
Mix 3	3661	3700	3556	-
CDF mould surfaces				
Mix 1	4395	4434	4439	-
Mix 2A	4592	4532	4274	-
Mix 2B	4569	4583	4483	-
Mix 3	4391	4026	2221	-

Table 7: Porosities, PF, densities and $m_{\text{suction}}/m_{\text{dry}}$

Mix	$\epsilon_{\text{suction}}$ (vol-%)	ϵ_{macro} (vol-%)	PF (%)	D dry (g/cm ³)	D solid (g/cm ³)	$m_{\text{suction}}/m_{\text{dry}}$
1 - 3C 25.1 I)	12.8	5.1	28.3	2.191	2.669	1.059
1 - 30 C 25.1	13.0	5.3	28.8	2.186	2.674	1.059
1 - 46 A	12.2	5.0	28.9	2.203	2.660	1.059
1 - 51 C 25.1	12.4	4.9	28.4	2.207	2.667	1.060
1 - 65 B 26.1	12.8	5.7	30.8	2.167	2.657	1.055
1 - 65C 26.1	13.0	5.5	29.9	2.165	2.658	1.056
Mix 1 (mean)	12.7	5.2	29.2	2.186	2.664	1.058
V (%)	2.6	6.1	3.3	0.8	0.3	0.2
2A - 3 C 27.1	11.7	3.0	20.5	2.279	2.672	1.051
2A - 30 C 27.1	11.3	2.6	18.8	2.302	2.672	1.049
2A - 46 C 27.1	11.3	2.7	19.3	2.291	2.666	1.050
2A - 51 C 27.1	11.1	2.8	20.3	2.297	2.667	1.051
2A - 65 B 28.1	11.3	3.0	20.8	2.289	2.672	1.049
2A - 65 C 28.1	11.7	2.8	19.3	2.284	2.673	1.048
Mix 2A (mean)	11.4	2.8	19.8	2.290	2.670	1.050
V (%)	2.3	5.5	4.0	0.4	0.1	0.1
2B - 3 C 2.1	11.4	3.0	20.8	2.286	2.670	1.050
2B - 30 C 2.1	11.5	2.8	19.4	2.289	2.672	1.050
2B - 65 B 9.3	11.6	3.2	21.8	2.274	2.670	1.051
2B - 65 C 9.3	11.8	3.0	20.6	2.279	2.675	1.052
Mix 2B (mean)	11.6	3.0	20.7	2.282	2.672	1.051
V (%)	1.3	6.2	4.8	0.3	0.1	0.1
3 - 46 C 3.2	13.4	2.7	16.8	2.237	2.666	1.060
3 - 51 C 3.2	13.2	2.9	18.0	2.235	2.665	1.059
3 - 65 C 9.3	13.5	2.6	16.0	2.236	2.665	1.060
3 - 82 B 9.3	13.6	2.7	16.3	2.227	2.659	1.061
Mix 3 (mean)	13.4	2.7	16.8	2.234	2.664	1.060
V (%)	1.1	5.1	5.1	0.2	0.1	0.1

- 1): The letters A, B or C indicate how the specimens were sawn from the 15 by 15 by 15 cm cubes:
A and C: one moulded side, B: center of cube
The last numbers indicate the dates of casting (as marked on the specimens).

6. DISCUSSION OF THE RESULTS

6.1 General

From table 7 it is seen that the concrete specimens received from VDZ/Germany were homogeneous both with respect to suction porosity (function of w/c, amount of cement and degree of hydration) and air void content. The scatter in scaling between companion specimens within one series in general seems to be low for the concretes with high scaling and higher for the concretes with low scaling.

Investigations of evaporation from the glue used for impregnation of the SS 13 72 44 specimens showed that the glue between concrete and rubber loses some weight. Direct comparison of the absorption values during test for the two test methods should therefore not be made. The longer time of presuction for the CDF - test and the presuction of 3 % NaCl instead of pure water also disturbs comparison of absorption during test for the two test methods. From table 6 it is seen how the rubber cloth reduces the pulse velocity: the pulse velocity values measured through the rubber cloth of the SS 13 72 44 specimens are reduced to 83 - 86 % of the values measured directly on the concrete surface of the CDF - specimens at start of test.

From table 4 it is seen that Mix 2A (3 % NaCl) has a very large (hundredfold) increase in scaling compared to Mix 2B (pure water), as expected. Mix 1 (3 % NaCl, air entrained concrete) is well protected by the air entrainment and has very low scaling even with 3 %

NaCl (as expected). Mix 3 ($w/c = 0.65$) was only tested with pure water and therefore there are no data on salt scaling for this concrete. However, for these test methods (SS 13 72 44 and the CDF - test) it is expected that Mix 3 would have even larger scaling than Mix 2A if tested with 3 % NaCl solution.

Comparison of the scaling of sawn and moulded surfaces (SS 13 72 44) in table 4 shows that moulded surfaces gave higher scaling for Mix 2A and 3, but only small differences for Mix 1 and 2B, meaning that moulded surfaces have higher scaling than sawn surfaces for these particular concretes. It should be taken into account that sawn surfaces has lower amount of cement paste exposed. For sawn surfaces also some scaling from non-frost resistant aggregate particles was observed.

By comparing the scaling of moulded surfaces for the two test methods (table 4), it is seen that SS 13 72 44 seems to be more severe than the CDF - test for Mix 2A (high scaling), while the differences between the two test methods for Mix 1, 2B and 3 (medium to low scaling) are small. However, test results with very high scaling such as for Mix 2A is of little importance when evaluating test results since for both test methods Mix 2A is far beyond the limit given in SS 13 72 44 for non-acceptable frost/salt scaling (1 kg/m^2).

From the ultrasonic pulse velocity measurements in table 6 and visual observations of cracks along edges of the top surfaces it is seen that for Mix 3 of the CDF test large internal cracking occurs after 56 cycles compared to the specimens tested by SS 13 72 44. It is therefore likely that the CDF - test is tougher than SS 13 72 44 with respect to internal cracking for this type of concrete. For the SS 13 72 44 test series Mix 2B (moulded test surfaces) were run up to a total of 250 cycles (Mix 3 unfortunately had leakage of water and was therefore stopped after 56 cycles). From tables 4, 5 and 6 it is seen that there are no signs of any sudden increase in damage, neither for scaling, absorption nor pulse velocity. The increase in scaling is small from start to 250 cycles. The results of absorption and pulse velocity measurements also seem to indicate that there are no sudden changes. The explanation for the increase in pulse velocity is not clear, but it could be due to continued hydration and/or increased water content. The reduction in pulse velocity observed for Mix 2A could be a result of the high scaling of this concrete; both scaling along edges and the mass reduction of the specimen could affect the ultrasonic pulse velocity after 56 cycles. The results therefore give no clear evidence of internal cracking in Mix 2A neither for SS 13 72 44 nor for the CDF-test. This is an example of high scaling but little internal cracking - the opposite of HSC with no scaling but extensive internal cracking /13, 14, 21/, indicating different mechanisms of deterioration in scaling and cracking tests.

6.2 Evaluation of the compensation of weight loss in scaled off mass

The relationship between the level of scaling and the absorption values in table 5 is estimated by comparing the corrected weight loss for test series with high and low scaling. In table 8 this is shown for four different test series.

Table 8: Effect of level of scaling on compensation of weight loss in scaled off mass.

Test		28 cycles (kg/m ²)	56 cycles (kg/m ²)
High scaling	scaling	6.71	11.13
Mix 2A	(x 1.050)		
SS mould	compensated	7.05	11.69
Medium/high scaling	scaling	1.91	5.78
Mix 2A	(x 1.050)		
CDF mould	compensated	2.01	6.07
Medium/low scaling	scaling	0.17	0.36
Mix 1	(x 1.058)		
CDF	compensated	0.18	0.38
Low scaling	scaling	0.04	0.06
Mix 2B	(x 1.051)		
SS mould	compensated	0.042	0.063

From table 8 it is seen that for the mix with 11.13 kg/m² scaling after 56 cycles the compensation adds 0.56 kg/m² to the weight of the specimen while 1.91 kg/m² after 28 cycles adds 0.10 kg/m² to the weight of the specimen. For a very low scaling of 0.04 kg/m² there is no effect within the precision of two digits after zero. The accuracy of the absorption values in table 5 for different levels of scatter between companion specimens in a test series will of course be proportional to the scatter of the scaling results within test series calculated in the same way as in table 8.

6.3 The importance of absorption during freeze/thaw testing

From table 5 it is seen that the absorption of salt solution/water is large after start of freeze/thaw testing compared to absorption during presuction for both test methods. This is in line with the observations made by Fagerlund, /8/. In table 9 scaling and absorption for all mixes are compared after 28 cycles.

Table 9: Scaling and absorption after 28 cycles (kg/m²)

		Mix 1	Mix 2A	Mix 2B	Mix 3	Δ(2A-2B)
SS 13 72 44 (Sawn surface)	Scaling	0.11	3.17	0.05	0.02	
	Absorption	0.80	0.90	0.57	1.06	0.33
SS 13 72 44 (Mould surface)	Scaling	0.08	6.71	0.04	0.11	
	Absorption	0.75	0.75	0.61	1.19	0.14
CDF - test (Mould surface)	Scaling	0.17	1.91	0.04	0.12	
	Absorption	0.30	0.64	0.46	0.99	0.18

From table 9 it is seen that the absorption in Mix 2A (3 % NaCl) is higher than Mix 2B (pure water) for all three test series (SS sawn and mould and CDF mould). The weight of the NaCl in the salt solution is too small to explain the higher absorption in the specimens tested with 3 % NaCl compared to those tested with pure water. (For air entrained concretes with the same mix composition (Mix 1) 2 of 3 test series with NaCl show higher absorption than the concretes without air tested with pure water. The reason for the relatively low absorption of Mix 1 in the CDF - test is not known). In the last column of table 9 the increase in absorption from Mix 2B to 2A is calculated. To illustrate the effect of

this increase in absorption on the degree of saturation in the top layer of the specimen we have made some simple calculations in table 10 assuming that the absorption is equally distributed in:

- a) the upper 2 mm of the specimen
- b) the upper 5 mm of the specimen

Table 10: Effect of increase in absorption on increase in saturation in the top layer of a specimen

Test	ΔS (2A-2B) kg/m ² S (3% NaCl) - S (H ₂ O)	ΔS (2A-2B) m ³ /0.0225m ²	Increase in S (vol-%)	
			a) 2 mm layer = 0.000045 m ³	b) 5 mm layer = 0.0001125 m ³
SS sawn	0.33	0.0000074	16.4	6.6
SS mould	0.14	0.0000032	7.1	2.8
CDF mould	0.18	0.0000040	8.9	3.6

From table 10 it is seen that the increase in absorption due to 3 % NaCl is more than enough to cause disruption of the concrete in the surface layer. From table 7 we see that the total porosity of Mix 2A/2B is about 14.5 %; 11.5 % suction and 3 % macro pores. The initial or actual degree of saturation was not measured, but the specimens had been air cured before testing (except for the first week, when they were stored in water according to the test specifications /11, 18, 19/). Thus, assuming an initial degree of saturation of 70 %, i.e. 10 % suction and macro pores empty, this implies more than enough increase in water content (2.8 - 16 % by volume) to completely saturate the surface layer. The calculations of table 10 therefore give good reasons to believe that the increase in absorption gives an important contribution to increased scaling in the presence of NaCl.

Comparison of scaling and absorption are made after 28 cycles. The reason for this is discussed in the following section: For Mix 2A there were some increased scaling along edges from 42 cycles due to high scaling for both test methods. For the CDF specimens of Mix 2A scaling along edges was also due to reduced bond between epoxy paint and concrete from 42 cycles. The implication of this observation is that the preparation system used in this particular test probably should not be used for CDF- testing of concrete with scaling larger than approximately 3.5 kg/m². (The authors experience is that problems with leakage of salt solution in the Borås method normally is associated with high scaling/poor concrete quality).

From tables 9 and 10 (comparing SS sawn and SS moulded surfaces) it can also be seen that the critical degree of saturation with respect to scaling is lower for the moulded surfaces than for the sawn surfaces since the level of absorption for a given amount of scaling is lower for the moulded surfaces. The reason for this can be that the surface concrete has been able to dry at early age and therefore is more poorly hydrated than the sawn surfaces which have hydrated in a state more close to sealed.

The reason for the increased degree of saturation in the presence of NaCl can be osmotic types of pressure arising from differences in concentration of soluble ions between ice and water in different parts of the pore structure/pores with different sizes (viz. gel and capillary pores). For the concretes with air entrainment (Mix 1) the air bubbles probably represent escape boundaries for expansion of ice at freezing. For concretes with pure water (Mix 2B, 3) the osmotic pressures that can arise will probably be much lower due to small

amounts of dissolved ions. According to Setzer /22/ the increased absorption during freeze/thaw can be explained by a pumping effect due to the high thermal expansion of water compared to ice, and the freeze/thaw hysteresis.

7. CONCLUSIONS

A limited literature survey of previous investigations on the absorption during frost/salt testing shows that the absorption during freeze/thaw in water or salt solution is higher than during isothermal absorption. Concrete freeze/thaw tested with salt solution absorbs more than concrete tested with pure water.

Previous laboratory data from frost/salt scaling tests show good relation between the amount of scaling and absorption during test for different concrete mixes.

Absorption during freeze/thaw test can be measured by adding the scaled off mass (dried at 105 °C) to the mass of the surface dry specimen after removal of scaled off concrete. The apparent weight loss observed when the scaling is quite high due to loss of w_e in the scaled off and dried concrete can be compensated for by multiplying scaled off mass by the ratio $m_{\text{suction}}/m_{\text{dry}}$ as calculated from porosity tests on parallel specimens.

Non - air entrained concretes tested with 3 % NaCl and pure water (Mix 2A, 2B) by two different frost/salt test methods (SS 13 72 44 and the CDF - test) showed that the concretes tested with 3 % NaCl had both higher scaling and higher absorption during test than the concretes tested with pure water. Calculations of increase in saturation in the surface layer show that the increase in saturation due to 3 % NaCl compared to pure water is high enough to cause disruption of the concrete. The results therefore confirm that the presence of NaCl during freezing results in higher degree of saturation compared to tests with pure water. Thus it is suggested that at least part of the increased scaling found with salt solution is caused by increased degree of saturation in the surface layer during the test.

Previous observations of high strength concrete with no scaling but extensive internal cracking, and the results of concretes with high scaling and no clear evidence of internal cracking implies that different mechanisms of deterioration dominate when testing cracking and scaling.

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9. ACKNOWLEDGEMENT

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