FROST/SALT SCALING OF NO - SLUMP CONCRETE: EFFECT OF STRENGTH, AIR ENTRAINING AGENT AND CONDENSED SILICA FUME

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ABSTRACT

The experiments presented were carried out to establish the possibility of producing frost/salt scaling resistant New Jersey type concrete safety barriers with no-slump concrete. New Jersey concrete safety barriers are commonly used along Norwegian roads and motorways but damages due to deicers and frost action have been a problem. Test production of concrete safety barriers has been carried out at two different manufacturers. The effects of high dosages of neutralized vinsol resin type air entraining agent (AEA) alone and in combination with condensed silica fume have been investigated. Frost/salt scaling resistance according to Swedish Standard SS 13 72 44 ("Borås - method") has been tested. Air content in hardened concrete has been measured with two different methods: PF - method (filling of air voids with water under pressure), and ASTM C 457 (optical). The results show increased air void content in no - slump concrete with air entraining agent compared to concrete without AEA, as measured with both PF-method and ASTM C 457. Plane sections show increased content of spherical air voids in concrete mixtures with AEA, but AEA does not seem to reduce the amount of irregular shaped compaction voids. Measurements of air voids optically and by water pressure show higher content of voids as measured optically. Testing of frost/salt scaling showed reduced scaling for concrete mixes with AEA compared to the same concrete mixes without AEA. Normal production concrete without AEA, having somewhat higher compressive strengths than test mixes, had lower frost/salt scaling than the SS 13 72 44 acceptance criterion (1 kg/m^2). Replacement of 4 % of the cement by weight with condensed silica fume resulted in 30 - 39 % increase in 28 day compressive strength. The results indicate that both strength and air content play important roles in the frost/salt scaling durability of no - slump concrete, and that it is possible to make frost/salt scaling resistant no-slump concrete both with and without the use of AEA.

Key Words: No-slump concrete, precast safety barriers, durability, frost/salt scaling, air entrainment, condensed silica fume, compressive strength

1 INTRODUCTION

Frost/salt scaling of precast concrete safety barriers of New Jersey type has been a problem along Norwegian roads and motorways. In an investigation by Sellevold /1/ it was stated that deteriorated concrete safety barriers generally had lower strength and lower air content than specified in the Norwegian road codes. Some of the investigated concrete safety barriers were made using no-slump concrete. It was suggested in /1/ that more and systematic knowledge is needed to establish which properties are important to make no-slump concrete frost/salt resistant, particularly with respect to a distinction between voids caused by incomplete compaction and proper airvoids. Earlier investigations on frost/salt scaling /9, 10, 4/ have indicated that high compressive strength leads to low frost/salt scaling.

The present paper describes the testing of no-slump concrete from New Jersey type safety barriers. Safety barriers were produced at two different manufacturers in Norway to study the effect of compressive strength, Air Entraining Agent (AEA) and Condensed Silica Fume (CSF) on the frost/salt scaling resistance and air content of no-slump concrete.

2 MATERIALS AND CONCRETE MIXES TESTED

At Factory A an ordinary Portland Cement (P 30) was used and at Factory B a modified Portland Cement (MP 30) containing 20 % fly ash was used. CSF with SiO_2 contents of 90.9 and 92.3 % were used. Characteristics of cements and CSF are given in Table 1. At both factories a calsium lignosulphonate based plasticizer with 40 % solids content and a neutralised vinsol resin type air entraining admixture (AEA) with 9 % solids content were used. Condensed Silica Fume was used as dry powder. At both factories the aggregate consisted of natural sand (0 - 8 mm) and crushed material (8 - 16 mm) of granitic rocks. The aggregate gradings for the combined aggregates are given in Table 2.

Three different concrete compositions were tested at each of the two factories to study the effect of AEA and CSF on frost/salt scaling resistance:

- Mixture 1: water reducing agent
- Mixture 2: water reducing agent and AEA,
- Mixture 3: water reducing agent, AEA and 4 % of the cement by weight replaced with CSF.

In Table 3 the concrete compositions tested in the investigations are given. Quite high dosages of AEA were used: 1.5 kg/m^3 concrete. The dosages of water reducing agent were 1 - 3 kg/m^3 concrete.

In addition to these test mixes, one safety barrier from each of the two factories made in normal production were tested. These two safety barriers had been stored outdoors for approximately 6 months each at their respective factories. The exact composition of these two safety barriers are unknown, but no AEA or CSF was used, and the materials (cement, aggregate, plasticizer) were the same as for the test mixes. The cement content of these safety barriers was probably somewhat higher and w/c - ratio lower than for the test mixes, as indicated by compressive strengths of cores.

Table 1: Characteristics of cements and CSF

	Cement			CSF	
	Factory A P 30	Factory B Cem. (80%)	MP 30 F.A (20 %)	Factory A	Factory B
Fineness (m^2/kg)	332	410		-	-
Setting time min.					
- initial	135	100		-	-
- final	205	145		-	-
Comp. strength (MPa)					
- 1 day	19	21		-	-
- 7 days	42	38		-	-
-28 days	51	48		-	-
Chem. composition (%)					
- SiO_2	19.8	20.7	58.0	90.9	92.3
- Al_2O_3	4.4	5.2	24.4	0.7	0.5
- Fe_2O_3	3.5	3.6	7.0	1.3	1.3
- CaO	62.6	64.0	1.7	-	0.3
- MgO	2.3	2.5	1.1	2.3	1.0
- SO_3	3.2	3.5	-	0.5	0.4
- K_2O	-	1.2	2.1	2.4	1.2
- Na_2O	0.8	0.5	0.4	0.5	0.6
- C	-	-	-	-	1.7
- SiC	-	-	-	-	0.6
- P_2O_5	-	-	-	-	0.1
- L.O.I.	1.2	0.2	-	2.1	2.2
Mineral Composition					
- C_3S	65.1	59	-	-	-
- C_2S	11.0	15	-	-	-
- C_3A	6.0	7.8	-	-	-
- C_4AF	11.6	10.9	-	-	-

Table 2: Aggregate gradings

ISO sieve (mm) % passing	0.125	0.25	0.5	1	2	4	8	16	FM (ISO)
Factory A	3.0	8.0	17.6	34.6	45.6	53.0	63.0	96.0	4.31
Factory B	3.4	7.0	8.1	25.3	37.1	47.0	62.7	96.0	4.65

Table 3: Concrete mix proportions used in the testing, kg/m^3 (excl. air voids)

Mix	Cement	CSF	W/C	P	AEA	Aggregate			ratio
						0 - 8	8 - 16	Total	0-8/8-16
Factory A	**P 30**								
Normal prod.	-	no		yes	no	-	-	-	-
- mix 1	339	-	0.41	3.0	-	1098	766	1864	59/41
- mix 2	339	-	0.39	1.5	1.5	1111	758	1869	59/41
- mix 3	321	11.4	0.40	1.5	1.5	1188	702	1890	63/37
Factory B	**MP 30**								
Normal prod.	-	no		yes	no	-	-	-	-
- mix 1	287	-	0.45	1.0	-	1152	938	2090	55/45
- mix 2	287	-	0.45	1.0	1.5	1158	939	2097	55/45
- mix 3	275	13.3	0.43	1.0	1.5	1150	937	2087	55/45

3 PRODUCTION OF CONCRETE SAFETY BARRIERS

The concrete used to produce the safety barriers had a very stiff consistency, i.e. no - slump concrete, in order to make it possible to demould the safety barriers immediately after filling and compaction. The concrete safety barriers weighed 2.2 tons each at Factory A (large "Oslo model") and 1.1 tons each at Factory B (small "Oslo model"). The members have the same length (2 m), but the small "Oslo model" has less volume than the large "Oslo model". Test safety barriers at Factory A were produced in June 1990 and at Factory B in August 1990. Safety barriers were produced by filling steel moulds during constant vibration. The vibration was provided from vibrators under the mould via the support of the mould at two points. After filling and compaction the mould was lifted and turned 180° and the safety barrier demoulded immediately. The safety barriers were stored the first 24 hours inside the factories, and then outdoors. No protection of the surface was provided during curing. Safety barrier and principle of production is shown schematically in figure 1.

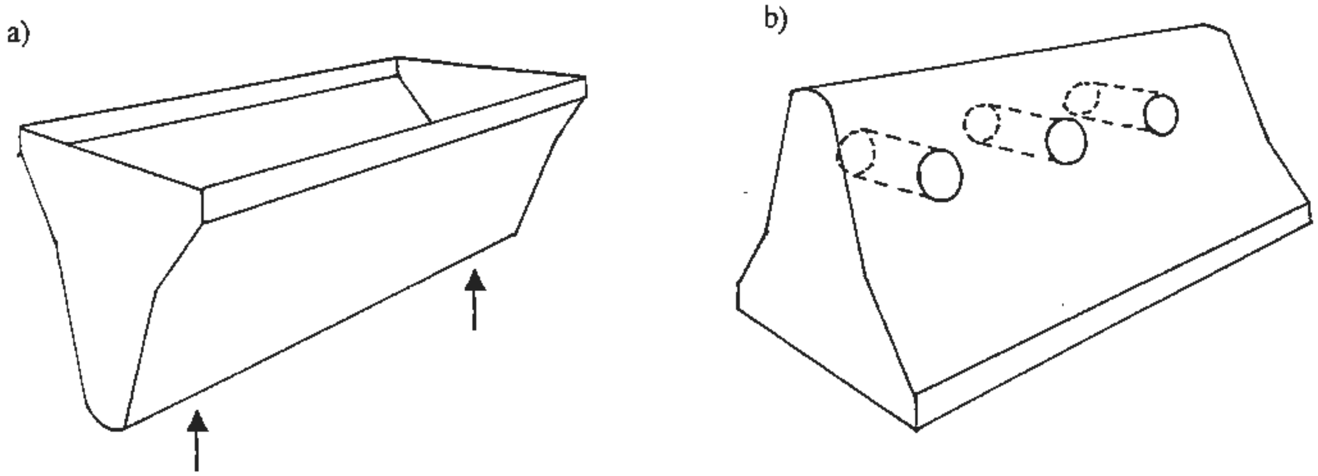


Figure 1: Production of concrete safety barriers, and cores for testing concrete

a) Mould for filling and compaction, vibration energy provided via supports in bottom
b) Demoulded safety barrier and positions of cores for testing of concrete

Mixing procedure consisted of 30 seconds mixing of dry materials, addition of water reducing agent and approximately half of the water during constant mixing (approximately 15 seconds), addition of AEA mixed with 5 - 10 liters of water/ m^3 concrete, and finally the rest of the water. Total mixing time with water was 1 minute. At the end of the mixing period a skilled operator evaluated whether the consistency was suitable for filling, compaction and immediate demoulding of concrete safety barriers. To obtain this, some "try and fail" mixtures were made with each of the different concrete compositions given in Table 3.

At both factories horizontal mixers with flat bottom and 1 m^3 batches of concrete were used. The vibration time of the safety barriers in the moulds were 3 - 4 minutes at each factory.

After demoulding the safety barriers, the temperature during the first 24 hours of hardening was recorded. This was done by inserting one thermocouple 10 - 15 mm under the surface and one thermocouple in the center of the safety barrier.

4 TEST PROCEDURES

100 mm diameter cores for testing were drilled 2 - 3 weeks after production. At Factory A three cores of length 400 mm were drilled, and at Factory B three cores of length 260 mm were drilled from each of the safety barriers. The length of the cores corresponded to the thickness of the safety barriers 30 - 40 cm from the top of the safety barriers. The differences in length of cores between Factory A and B are due to the different sizes of the safety barriers. In figure 1 the location of cores on the safety barriers are shown. After drilling the cores were stored in airtight plastic bags and sent to the laboratory. In the laboratory specimens for the different tests were sawn from the cores. From each of the safety barriers specimens were prepared for investigation of frost/salt scaling resistance according to Swedish Standard SS 13 72 44 ("Borås - method") /2/, 28 day compressive strength and air content of hardened concrete according to the PF - method /3/. In addition, air content and air void structure of hardened concrete were investigated on Mixture 1 and 2 (eg. concrete without and with AEA) from each of the two factories according to ASTM C 457. In Table 4 size and amount of specimens for the different tests are shown.

Table 4: Sawing of cores for laboratory testing (all cores diameter 100 mm)

Test	No. of cores per mix	Height of specimen (mm)	Comment
Frost/salt scaling	6	50	Moulded surfaces tested
Compressive strength and density	Fact.A: 3 Fact.B: 2	100	Height/Diameter=1.0
Air content (PF -method), 30 min water absorption	Fact.A: 3 Fact.B: 2	30	Next to frost/salt specimens
Air void content ASTM C 457	1	-	20 mm below surface of frost/salt specimen

Frost/salt scaling tests

Frost/salt scaling tests were performed according to Swedish Standard SS 13 72 44 on specimens cut from the cylinders. 25 days after production, specimens for testing were sawn according to table 4. Six parallel specimens with moulded surfaces were tested for each mixture. After sawing, the specimens were stored at 50 % relative humidity and 23 °C for 11 days. After that the specimens were prepared as shown in figure 2 and stored for 3 days with fresh water on the surface of the specimens. After 3 days the fresh water was removed and a 3 mm layer of 3 % NaCl solution was put on the surface. The freeze/thaw testing started immediately afterwards according to the temperature - time cycle shown in figure 3. Scaled-off concrete was measured after 7, 14, 28, 42 and 56 cycles and calculated per unit area.

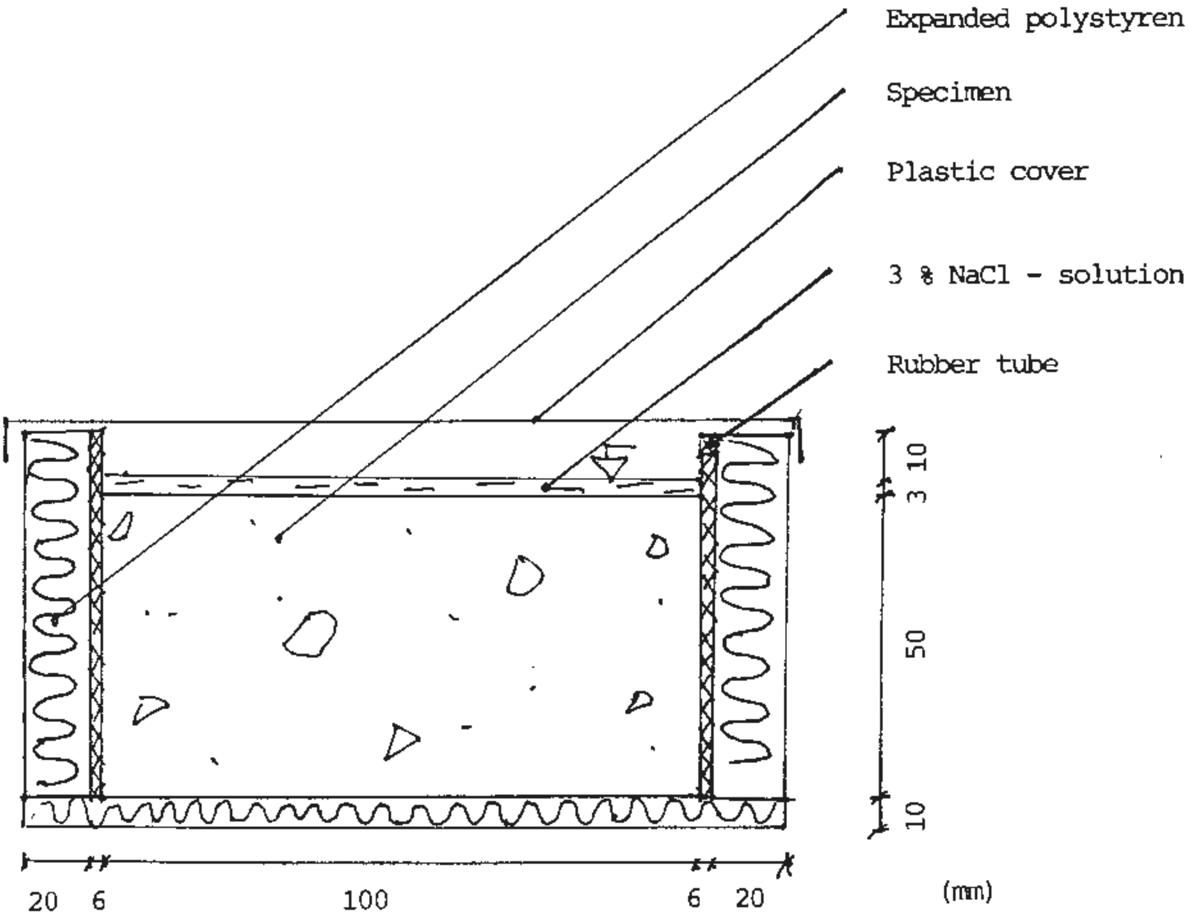


Figure 2: Preparation of specimens for SS 13 72 44 freeze/thaw test

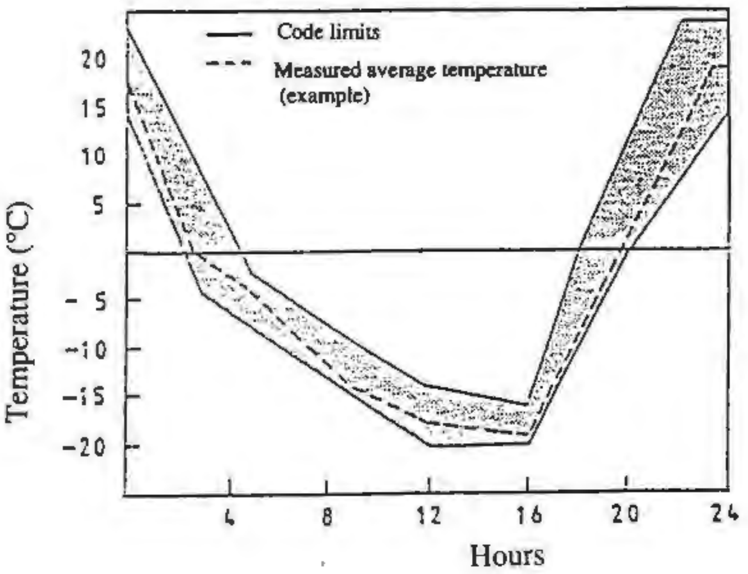


Figure 3: Freeze/thaw cycle according to SS 13 72 44

Compressive strength and density

For each mixture three parallel specimens were sawn after 25 days according to table 4. The sawn surfaces were ground to assure a height/diameter - ratio of 1.0 and that the test surfaces were parallel. The specimens where then stored in water at 20 °C for 3 days until testing. Density of specimens for compressive strength was measured by weighing the specimens in air and in water before testing compressive strength.

Air content of hardened concrete - PF-method

Air content of hardened concrete was measured according to the PF-method /3/ on 30 mm thick slices. The testing procedure consists of measuring the weight of a concrete specimen in different moisture conditions, measuring the volume and then calculating porosities and densities from these data:

Weight A:	Dried to constant weight (105 °C)
Weight B:	After immersion in water
Weight C:	Pressure saturated (10 MPa water pressure)
Volume V:	Weighing in water

The following porosities are calculated:

Suction porosity = (B - A)/ V (%)
Air content = (C - B)/ V (%)

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 after immersion in water (capillary suction), but are filled after application of 10 MPa water pressure. In addition different densities can be calculated from the data. Sellevold /3/ has documented that air content measured with the PF-method and air content measured optically on plane sections correlate very well. In addition the specimens were weighed after 30 minutes immersion in water. This was done to compare the rate of absorption for the different mixtures. Earlier work has indicated good correlation between rate of absorption and compressive strength /1/.

Air content of hardened concrete - optical method

This was measured on mixture 1 and 2 for both factories. The measurement was performed on specimens for frost/salt scaling testing after the frost/salt scaling test was finished. One single specimen from Mix 1 and 2 from each of the two factories were sawn 20 mm from test surface and parallel to the test surface. The specimens were prepared as plane sections (polished and impregnated with fluorescent epoxy resin) and air content and air void structure were measured according to ASTM C 457 - linear traverse method. In addition the air void systems were evaluated on the plane sections by a qualitative classification into irregular compaction voids or spherical air voids, and typical areas of the concretes were photographed.

5 RESULTS AND DISCUSSION

The maximum observed curing temperatures on the surface were 43 °C at Factory A and 25 °C at Factory B. Maximum observed temperatures in the center of the safety barriers were 54 °C at Factory A and 34 °C at Factory B. Air temperatures the first 24 hours varied between 15 - 21 °C at Factory A and 20 - 21 °C at Factory B.

It has been shown earlier /4/ that an increase in curing temperature from 20 to 45 °C results in increased frost/salt scaling for non-air entrained concrete with w/c = 0.45, whereas concrete with 8 % CSF and W/(C+S) = 0.45 had lower increase in scaling. In this investigation any possible effects of curing temperature on frost/salt scaling would be expected to be present for Factory A which had the highest curing temperature at the frost/salt scaling tested surface.

In table 5 frost/salt scaling results are shown, and plotted in figure 4 and 5 as scaling versus number of cycles. The results show lower scaling for corresponding mixes at Factory A compared to Factory B. Normal production safety barriers from both factories have lower scaling than the acceptance criterion 1 kg/m^2 after 56 cycles in /2/. At Factory A Mix 1 (without AEA) has 1.67 kg/m^2 after 56 cycles, whereas Mix 2 (with AEA) has 0.20 kg/m^2 after 56 cycles. Mix 3 (AEA and 4 % CSF) has 0.17 kg/m^2 after 56 cycles. At Factory B Mix 1 (without AEA) has 3.28 kg/m^2 , Mix 2 (with AEA) has 2.52 kg/m^2 and Mix 3 (AEA and 4 % CSF) has 3.00 kg/m^2 after 56 cycles. Considering the standard deviations there are hardly any significant differences in scaling between Mix 2 (AEA) and Mix 3 (AEA and CSF) for any of the factories.

Table 5: Scaled off mass (kg/m^2) for the tested concretes - accumulated

Specimen	Accumulated scaling (kg/m^2)									
	7	SD	**14**	SD	**28**	SD	**42**	SD	**56**	SD
Factory A										
Normal prod.	**0.06**	0.05	**0.19**	0.17	**0.45**	0.29	**0.54**	0.33	**0.70**	0.40
Mix 1	**0.26**	0.15	**0.66**	0.23	**1.11**	0.35	**1.46**	0.46	**1.67**	0.59
Mix 2	**0.09**	0.02	**0.13**	0.04	**0.18**	0.03	**0.19**	0.03	**0.20**	0.03
Mix 3	**0.09**	0.02	**0.12**	0.03	**0.14**	0.03	**0.15**	0.04	**0.17**	0.06
Factory B										
Normal prod.	**0.17**	0.02	**0.29**	0.04	**0.43**	0.03	**0.60**	0.09	**0.77**	0.19
Mix 1	**0.97**	0.53	**2.22**	0.27	**2.74**	0.35	**3.10**	0.31	**3.28**	0.26
Mix 2	**0.24**	0.11	**0.83**	0.48	**1.74**	0.47	**2.29**	0.28	**2.52**	0.19
Mix 3	**1.25**	0.51	**1.58**	0.55	**2.23**	0.71	**2.54**	0.61	**3.00**	0.59

SD: Standard deviation 6 parallel specimens

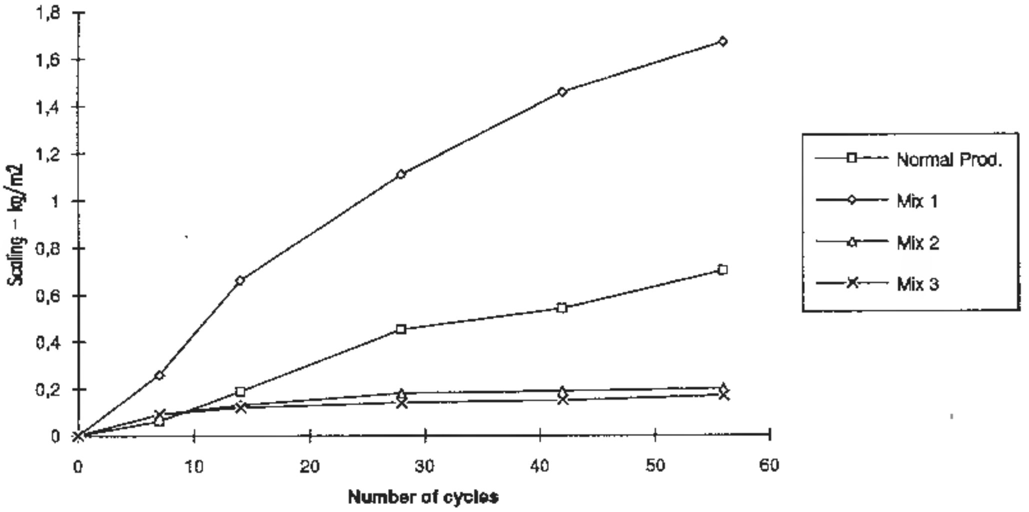


Figure 4: Scaling vs. number of cycles for concrete from Factory A

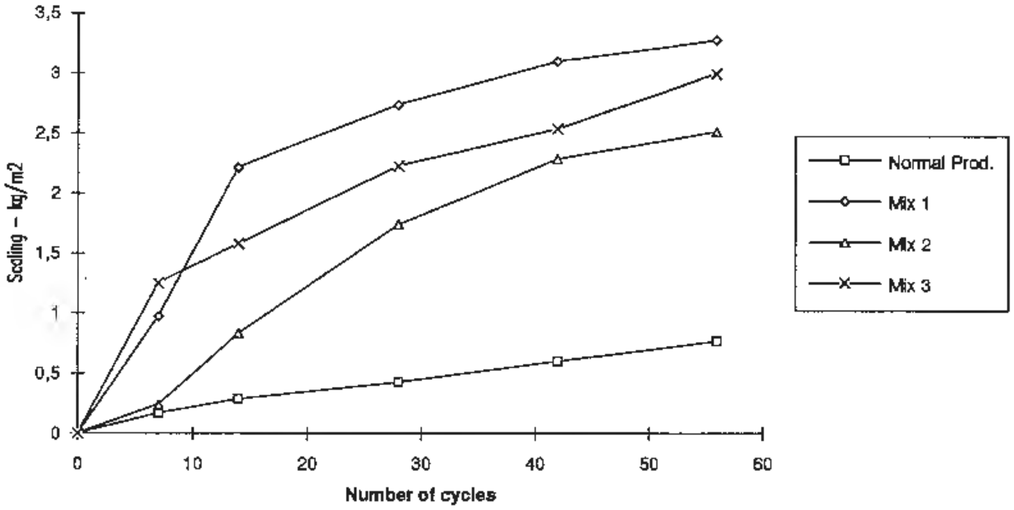


Figure 5: Scaling vs. number of cycles for concrete from Factory B

In table 6 compressive strengths are given. The normal production safety barriers have the highest compressive strengths, and both perform satisfactory in the Borås test. The test mixes at Factory A have 48 - 58 % higher strength than the Factory B mixes. By comparing Mix 3 and Mix 2 for both factories it is seen that CSF gives 30 - 39 % increased strength. This is more than would be expected in concrete with flowing consistency by replacing 4 % of the cement with CSF, /5/. At Factory A the density for Mix 2 is lower than for Mix 3, but at factory B the density for Mix 2 is a little higher than for Mix 3, see table 6. Air contents for Mix 2 and Mix 3 were approximately the same at both factories, see table 7. Density and air content of the hardened concrete therefore do not explain the surprisingly high strength gain by the addition of 4 % CSF. We have no certain explanation for this observation. High strength gain in no-slump concrete (19 -64 %) due to relatively small amounts of CSF (2 - 6 %) has earlier been reported by Horrigmoe et al, /6/.

Table 6: Compressive strength (MPa) and density (kg/m^3)

Mix	strength	strength	density	age
Factory A		(relative)		
Normal prod.	**57.8**		2360	ca. 6 months
Mix 1	**50.9**		2420	28 days
Mix 2	**36.9**	1.00	2340	28 days
Mix 3	**47.9**	1.30	2380	28 days
Factory B				
Normal prod.	**56.1**		2440	ca. 6 months
Mix 1	**32.3**		2420	28 days
Mix 2	**23.3**	1.00	2380	28 days
Mix 3	**32.4**	1.39	2370	28 days

In table 7 air void content measured with the PF method is given. By comparing mix 2 and mix 3 (AEA) to mix 1 (no AEA) it is seen that for both factories there is an increase in air content of about 2.5 % by use of AEA. The normal production concretes show 5.1 % air voids at Factory A and 2.9 % air voids at Factory B. None of the two normal production safety barriers contain AEA. 30 minutes water absorption and total suction porosities are reduced by use of AEA. Unlike the finding in /1/ there is no correlation between 30 minute absorption and strength for these concretes with and without AEA and CSF.

Table 7: PF - method: 30 - min. absorption, total suction porosity and air void content

Mix	Porosity (Volume - %)		
	30 min abs.	Tot.suction	**Air void**
Factory A			
Normal prod.	-	10.4	**5.1**
Mix 1	5.9	10.8	**4.2**
Mix 2	4.7	10.2	**6.9**
Mix 3	3.8	10.1	**6.7**
Factory B			
Normal prod.	-	11.4	**2.9**
Mix 1	5.8	9.5	**3.4**
Mix 2	4.9	9.0	**5.6**
Mix 3	4.0	9.3	**5.9**

In table 8 air void content and air void structure measured optically for Mix 1 and 2 at both factories are given. In table 9 air void contents of Mix 1 and Mix 2 measured by both methods from the two factories are compared. It is seen that the optical method for all four mixes measures higher air void content than the PF - method. The explanation is probably that the PF - method does not detect open compaction voids as air voids. These open compaction voids are probably already filled during water suction and therefore not registered as air voids. An increase in air void content was measured from Mix 1 (without AEA) to Mix 2 (AEA) at both factories also with the optical method. Specimens for measurements with the PF-method were taken next to the surface on which ASTM C 457 measurements were made (approximately 30 mm) according to table 4. Possible differences in air content in different parts of each core have not been investigated.

Table 8: Air content measured according to ASTM C 457

Mix	Total air content (%)	Specific surface (α - 1/mm)	Spacing factor (L - mm)
Factory A			
Mix 1 (without AEA)	4.8	4.04	1.15
Mix 2 (AEA)	12.1	9.76	0.25
Factory B			
Mix 1 (without AEA)	7.1	6.60	0.46
Mix 2 (AEA)	7.9	13.98	0.18

Table 9: Air content measured optically ($A_{ASTM\ C457}$), by PF - method (A_{PF}) and difference (A_{DIFF})

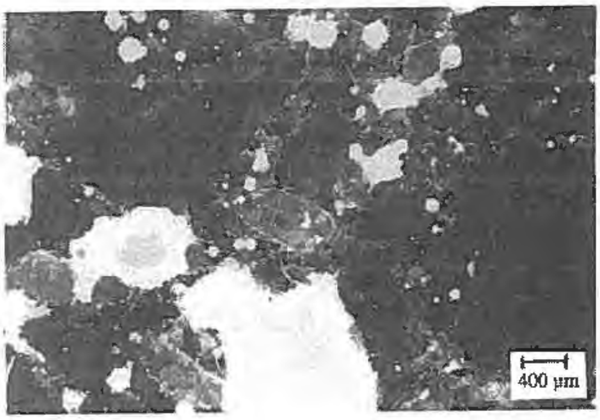
Mix	Air content (%)		
	$A_{ASTM\ C457}$	A_{PF}	A_{DIFF}
Factory A			
Mix 1	4.8	4.2	0.6
Mix 2	12.1	6.9	5.2
Factory B			
Mix 1	7.1	3.4	3.7
Mix 2	7.9	5.6	2.3

In figure 6 photos of typical areas of the plane sections are shown. At both factories it was observed that Mix 2 (with AEA) had a much higher amount of spherical air voids than Mix 1 (without AEA). The amount of irregular shaped compaction voids did not seem to be reduced by the use of AEA. Compaction voids measuring up to 3 mm in cross section were observed in Mix 1 and Mix 2 from both factories. Mix 3 (CSF) and normal production concretes were not investigated by ASTM C457. At air void measurement according to ASTM C457 no distinction was made between spherical air voids and irregular shaped compaction voids. The results in table 8 show reduced spacing factors for both mixes with AEA compared to mixes without AEA. The mixes with AEA also showed reduced scaling, indicating that the AEA has resulted in a more protective air void system.

Figure 6: Photos from plane sections

a) Factory A - Mix 1 (no AEA)

Large compaction void

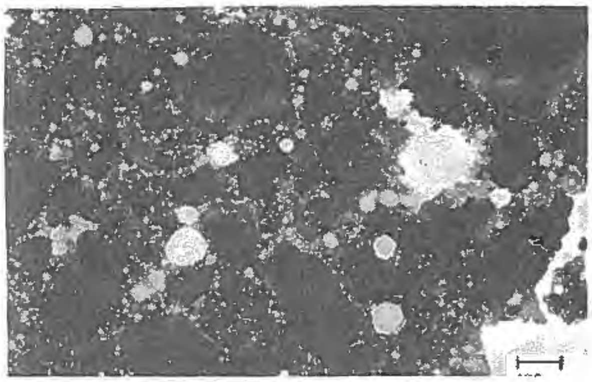


b) Factory A - Mix 2 (with AEA)

Compaction voids 0.1 - 1 mm
spherical air voids 50 - 200 µm

c) Factory B - Mix 1 (no AEA)

Compaction voids 200 - 500 µm



d) Factory B - Mix 2 (with AEA)

Part of large compaction void (ca. 3 mm) in lower right corner, and
spherical air voids 50 - 300 µm

The importance of entraining the right air void system for frost resistant no-slump concrete has been demonstrated earlier by Nischer /7/ and Marchand et. al /8/. In /7/ it was shown that it is possible to entrain spherical air voids in no-slump concrete for precast concrete blocks. The investigation /7/ showed that a spacing factor based on only spherical air voids (excluding compaction voids) should be used. Concrete blocks with low spacing factors (based on spherical air voids) and high content of spherical air voids compared to amount of compaction voids, were frost/salt scaling resistant according to an Austrian frost/salt scaling test. In /8/ it was pointed out that it is very difficult to obtain a proper system of spherical air voids in roller compacted concrete for pavements.

The results from the present frost/salt scaling tests indicate that both strength and air content play important roles in assessing the frost/salt scaling resistance for no - slump concrete. The explanation for the lower strengths and higher scaling of the test safety barriers at Factory B lies most probably in higher w/c - ratios due to lower cement content than at Factory A. Test safety barriers from Factory B had 50 kg/m^3 less cement than at Factory A, see table 3.

It is the authors experience from earlier investigations /4, 9, 10/ that high compressive strength implies low ice formation and good frost/salt scaling resistance. The investigations presented in this paper support these findings; that it is possible to make frost/salt scaling resistant concrete without AEA if the concrete strength is sufficiently high. The importance of good compaction for good frost/salt durability of roller compacted concrete has been pointed out /6, 11/. However the function of the compaction pores in no - slump concrete during freezing and thawing is not fully understood. Simultaneous investigations of frost/salt scaling and water saturation is one of the investigations that should be performed to study this further. The importance of the degree of saturation for assessing frost resistance of concrete has been shown by Fagerlund /12/. However, differences in mechanisms of damage with and without deicing salts are probably not completely understood yet.

6 CONCLUSIONS

Frost/salt scaling testing according to Swedish Standard SS 13 72 44 and measurements of compressive strength and air void content with two methods (ASTM C457 and PF-method) demonstrate that both strength and air content play important roles in assessing the frost/salt scaling resistance of no - slump concrete. The results indicate that it is possible to improve frost/salt scaling durability of no-slump concrete by use of high dosages of air entraining agent (AEA). The results from the normal production safety barriers indicate that it is possible to make frost/salt scaling resistant no-slump concrete without AEA if the compressive strength is high enough (i.e. sufficient compaction and low w/c -ratios).

No significant effect on frost/salt scaling was observed from Mix 2 (AEA) to Mix 3 (AEA and condensed silica fume (CSF), 4 % replacement by weight). Low compressive strengths for the test safety barriers from Factory B due to higher w/c - ratio are probably responsible for only a small reduction in scaling for air entrained concrete from this factory.

Qualitative inspection of plane sections show that AEA has increased the amount of spherical air voids, and that AEA does not reduce the amount of irregularly shaped compaction voids. By comparing air void content measured by two methods (optically and by water pressure), the results indicate that part of the air voids are open compaction voids that are filled with water during immersion in water.

Replacement of 4 % of the cement with CSF in addition to AEA resulted in 30 - 39 % increase in compressive strength compared to addition of AEA alone. Density and air content of the hardened concrete do not explain the surprisingly high strength gain by the addition of 4 % CSF. We have no certain explanation for this observation.

7 REFERENCES

/1/ Sellevold E.J.: Investigation of concrete quality in New Jersey safety barriers, NBI report O 1746, The Norwegian Building Research Institute 1986 (In Norwegian)

/2/ Swedish Standard SS 13 72 44: Testing of hardened concrete - Frost resistance, Standardiseringskommisionen i Sverige, 1988

/3/ Sellevold E.J.: Hardened Concrete - Determination of air/macro and gel/capillary porosity (PF - method), NBI report O 1731, The Norwegian Building Research Institute 1986 (In Norwegian with appendix draft method in English)

/4/ Sellevold E.J., Jacobsen S.: Ice formation and frost/salt scaling of concrete: Effect of curing temperature and condensed silica fume on normal and high strength concrete. Proceedings from a Nordic seminar in Borås 29 - 30 October 1991. Editor: Per Erik Petersson, Swedish National Testing and Research Institute report 1991:32.

/5/ Sellevold E.J.(Main author): Condensed Silica Fume in Concrete: A World Review. FIP State-of-the-art report, Thomas Telford, London, 1988.

/6/ Horrigmoe G., Brox Rindal D.: High Strength Roller Compacted Concrete, 6th International Symposium on Concrete Roads, Madrid, Spain, October 8 - 10 1990.

/7/ Nischer P.: Herstellung und Uberwachung von Luftporenbeton bei Betonsteinen (Production and control of air entrained concrete for concrete blocks) Betonwerk + Fertigteil - Technik 12/1974 (In German with summary in English) pp. 761 - 765

/8/ Marchand J., Pigeon M., Isabelle H.L., Boisvert J.: Freeze-Thaw Durability and Deicer Salt Scaling Resistance of Roller Compacted Concrete Pavements. Proceedings of the Paul Klieger International Symposium on the Performance of Concrete, San Diego, USA 1989, ACI SP-122 pp.217-236.

/9/ Sellevold E.J., Farstad T.: Frost/salt Testing of Concrete: Effect of Test Parameters and Concrete Moisture History, Nordic Concrete Research, Publication no. 10 1991 pp.121 - 138.

/10/ Hammer T.A., Sellevold E.J.: Frost Resistance of High Strength Concrete, 2nd International Symposium on High Strength Concrete, Berkeley, USA, 1990.

/11/ Marchand J., Pigeon M., Isabelle H.L.: The Frost Durability of Dry Concretes Containing Silica Fume, Paper presented at the Second CANMET/ACI International Workshop on the use of Silica Fume In Concrete, Washington D.C., USA April 3 - 9 1991

/12/ Fagerlund G.: Studies of the destruction mechanism at freezing of porous materials. Paper presented at the 6th international congress on problems raised by frost action. Le Havre April 23 to 25 1975, Swedish Cement and Concrete Research Institute report 1:76.

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