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Internal frost resistance and salt frost scaling of self-compacting concrete

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Abstract

This article outlines laboratory and analytical studies of salt frost scaling and internal frost resistance of self-compacting concrete (SCC) that contains increased amount of filler, different air content, and dissimilar methods of casting. The results were compared with the corresponding properties of normal concrete (NC) with the same water-to-cement ratio (0.39) and air content (6%). The start of the testing was applied at ages of 28 and 90 days. The strength development of the concrete was followed in parallel. Six SCC and two NC were studied. The effects of normal and reversed order of mixing (filler last), increased amount of filler, fineness of filler, limestone powder, increased air content, and large hydrostatic concrete pressure were investigated. The results indicated a substantial improvement of the internal frost resistance of SCC as compared to NC. The salt frost scaling performed more or less in the same way in SCC and in NC. No relationship of frost resistance was found to the air-void structure of the concrete.

Keywords: Aging; Concrete; Durability; Freezing and thawing; Long-term performance

1. Background and objective

Self-compacting concrete (SCC) is a type of concrete that does not require any energy for compacting in order to cover the reinforcement or fill out the mould has attracted a great deal of interest. Nineteen full-scale bridges and other full-scale projects that used SCC are now existent in Sweden [1]. The technique has also been introduced for dwelling houses and office buildings [2]. Currently, about 5% of the Swedish concrete production are SCC. The durability of concrete exposed to severe circumstances like bridges, dams, tunnel, and so forth should be superior [3]. Therefore, a higher level of documentation is required for concrete under severe conditions than for concrete that is used for dwelling houses or office buildings. The primary durability properties are salt frost scaling, internal frost resistance, sulphate resistance, and chloride ingress. In this study, the objectives were to investigate the salt frost scaling and the internal frost resistance of SCC that contains increased amount of filler, different types of casting, and air content and to compare the result with the corresponding properties of normal concrete (NC).

2. Previous research

In a recent study, the effect of fly ash, ground blast furnace slag, and silica fume on the salt frost scaling of SCC was investigated [4]. Table 1 shows the mix proportions in this study. The air content of all the studied concrete was about 6%. Salt frost scaling increased with large amounts of slag compared with the corresponding scaling of Portland cement concrete (Fig. 1) [4]. For SCC with 12% fly ash and 5% silica fume as calculated on the cement content, less salt frost scaling was observed than for an NC without those additives; however, for SCC with 24% fly ash and 10% silica fume, larger salt frost scaling was obtained than for the NC (Fig. 1). The salt frost scaling is not only dependent on the type of binder but may also be dependent on the air-void system created in the concrete. In another study, salt frost scaling and internal frost resistance of SCC and NC were compared [5]. Mix composition, salt frost scaling, length change, and change of fundamental transversal frequency are shown in Table 2. The fundamental transversal frequency gives a measurement of dynamic elastic modulus, which is a quantity of the internal damage caused by frost. The following conclusion were drawn [5]:

1. Frost scaling and fundamental transversal frequency loss were larger for NC than for SCC.

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Table 1
Mix composition and other properties [4]

Material/mix composition	D	F	G	RO II	T
Crushed aggregate Bålsta 8–16	496	494	580	876	495
Natural sand Bålsta 0–8	699	728	800	727	714
Natural sand SÄRÖ 0–2	505	465	220	149	521
Fly ash	89	55			
Glass filler			60		
Cement Aalborg (CEMI)	375				
Cement Degerhamn (CEMI)		440	420	438	
Slag cement (CEMIII, 68% slag)					470
Silica fume Elkem (granulate)	35	18	21		
Air entrainment (g, 10% dry)	0.498	0.501	0.500	482	0.498
Superplasticiser (35% dry)	5.25		4.24	5.92	3.52
Water	191	172	162	171	183
Water-to-binder ratio	0.38	0.38	0.37	0.39	0.39
Slump flow (mm)	690	725	720	150	737
Density	2247	2300	2306	2368	2281
Aggregate content (>0.125, vol.%)	0.64	0.64	0.60	0.66	0.65
Air content (%)	6.4	6.2	6.3	6.1	5.7
28-Day cube strength (100 mm, MPa)	61	70	64	63	79

Table 2
Mix composition, increase in length, and frost resistance [5]

Material, cement type, water-to-cement ratio	BAP3	BAP5	HPC
Coarse aggregate 6–14 mm	267	267	
Sand 3–6 mm	543	544	
Sand 0–4 mm	886	887	
Limestone powder	101	100	
Cement CEMI 52.5 R	352	350	323
Plasticiser	3.2	5.0	
Superplasticiser	2.3	0.9	
Water	197	190	
Water-to-cement ratio	0.56	0.54	
Water-to-powder ratio	0.44	0.42	
Aggregate content (>0.125 mm, vol.%)	0.64	0.64	
Slump flow (mm)	600	580	
28-Day strength (MPa)	56	58	72
Decrease of transversal resonance (%)			
150 frost cycles	0	13	100
300 frost cycles	7	18	–
Increase of length (%)			
150 frost cycles	0.01	0.13	0.39
300 frost cycles	0.01	0.22	–
Salt frost scaling (kg/m^2)			
28 frost cycles	0.9	1.3	1.8
56 frost cycles	0.9	1.4	3.7

2. Salt frost scaling increased with time for NC but remained constant for SCC at 0.9 kg/m^2, which was obtained already after 28 cycles.
3. NC exhibited a total loss of the internal solidity after 150 frost cycles while SCC lost only 7% of the cohesion (elastic modulus) during the corresponding period.
4. After 300 frost cycles, the decline of the elastic modulus was only 12% of SCC.

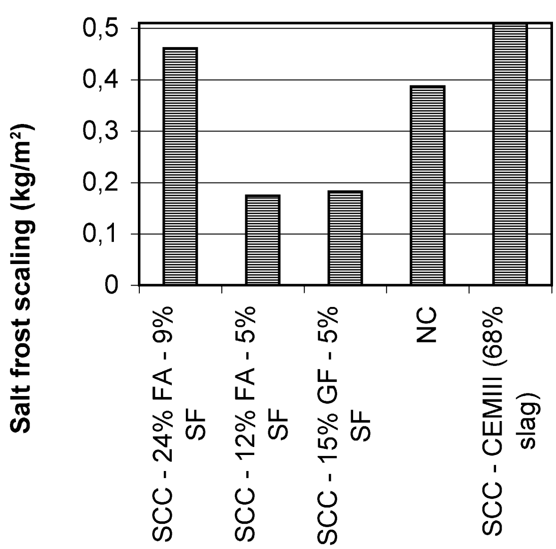

Fig. 1. Salt frost scaling of NC and SCC with additives (Table 1) [4]. FA = fly ash; GF = glass filler; SF = silica fume.

3. Materials and methods

3.1. Materials

Crushed gneiss (elastic modulus 60 GPa and strength 230 MPa), natural sand, limestone filler Limus 15 or 40, and Portland cement CEM I42.5BV/SR/LA Degerhamn were used (Table 3). Melamine-based superplasticiser was used for NC (branch Flyt 97M), polycarboxyl ether for SCC (branch Glenium 51), and an air-entrainment agent based on fir oil and fatty acids (branch Microair). Manufacturing and curing specimen were performed in the following way:

1. A new mixing order (N) was done on all dry materials except for the filler, which was mixed for 1/2 min with water and air entrainment. Then, half the amount of superplasticiser was mixed for 1/2 min [6].
2. Finally, the remaining superplasticiser with filler was mixed for 2 min [6].
3. An ordinary mixing order (O) was done with all dry materials at the start, which was mixed for 1/2 min with water and air entrainment. Then, all the materials with the superplasticiser were mixed for 2 1/2 min.

Table 3
Mix composition and properties [8]

Material/mix composition	KN	KOB	KN8	KO	KOT	SO	RO	ROII
Crushed aggregate Bålsta 8–16	363	371	355	367	363	402	862	876
Natural sand Bålsta 0–8	853	872	836	864	855	786	715	727
Natural sand SÄRÖ 0–2	316	135	309	320	316	422	146	149
Limestone filler	183	375	180	186	184	94	0	
Cement Degerhamn	418	427	409	423	419	416	431	438
Air entrainment (g, 10% dry)	585	213	1203	106	117	125	474	482
Superplasticiser (35% dry)	2.97	4.13	3.2	3.39	3.69	2.99	7.32	5.92
Water	163	167	160	165	163	162	168	171
Water-to-cement ratio	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Air content (%)	5.6	4.9	8	5.5	6.3	5.6	5.8	6.1
28-Day cube strength (MPa)	63	84	50	75	75	61	68	63
Slump flow (mm)	720	780	735	620	640	710	110	150
Density	2297	2348	2250	2323	2300	2285	2325	2368
Aggregate with filler (vol.%)	0.643	0.654	0.630	0.652	0.645	0.641	0.650	0.661

B = increased amount of filler; K = Limus 40 limestone filler; N = new way of mixing (filler at last); O = ordinary way of mixing (filler first); R = normal; S = Limus 15 limestone filler; T = 5.5 m hydrostatic pouring pressure instead of 0.23 m; II = second; 8 = 8% air content.

4. The specimen was cast in steel mould with a diameter of 0.23 m and length of 0.3 or 6 m.
5. NC was vibrated 10 + 10 + 10 s (SCC was not vibrated).
6. Sealed curing at 20 °C was done until small specimens were core-drilled from the large specimen.

The following specimens were core drilled at 28 and 90 days of age:

1. for the salt frost scaling: three discs with a diameter of 94 mm and length of 40 mm;
2. for the internal frost resistance: three cylinders with a diameter of 50 mm and length of 150 mm;
3. when testing the effect of hydrostatic pressure, the specimen was cored 0.5 m from the bottom of the 6-m-long vertical specimen;
4. between drilling and testing, the cylinders were stored in water saturated by adding limestone powder.

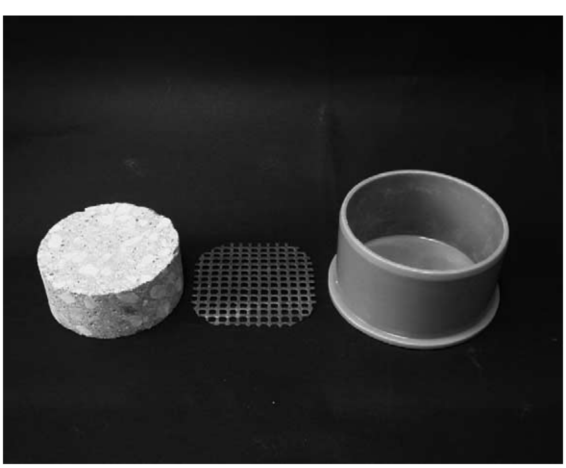

Fig. 2. Specimen for tests of salt frost scaling [7].

3.2. Methods

Salt frost scaling was studied by a method previously used by Lindmark [7]. The specimen was placed in a plastic container and fully immersed into 3% NaCl (Fig. 2). Two frost cycles daily varying between − 20 and 20 °C were used. The temperature was held at − 20 °C and 20 °C internally for 3 h. The tests were started either at 28 or 90 days of age. The salt frost scaling was determined after 28, 56, and 112 frost cycles by weighing. During the investigation of the internal frost resistance, the specimen was placed

Fig. 3. Specimen in a rubber container, fully immersed into distilled water [8].

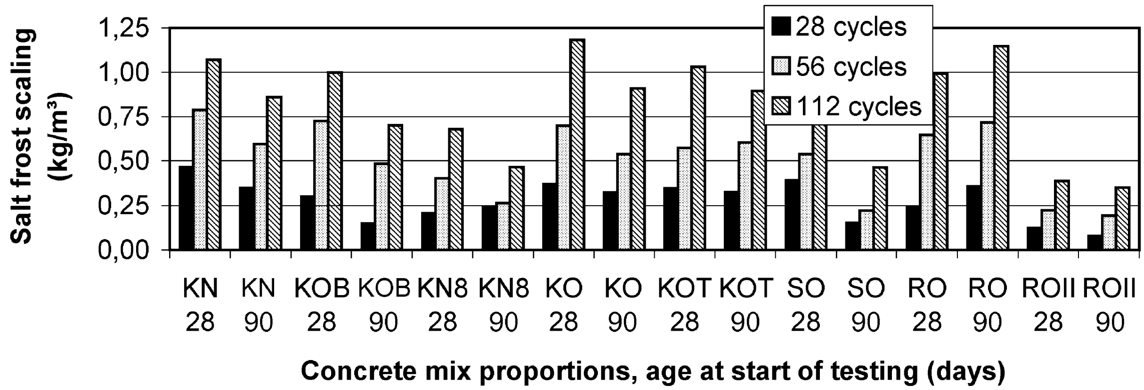

Fig. 4. Salt frost scaling of NC and SCC. Mix proportions and notations given in Table 3.

in a rubber container and fully immersed into distilled water (Fig. 3) [8]. Two frost cycles daily varying between − 20 and 20 °C were used. The tests were started either at 28 or 90 days of age. The frost scaling was determined after 100 and 300 frost cycles by weighing. The decrease of the elastic modulus due to internal damages was obtained by measurement of the fundamental resonance frequency in a Grindosonic apparatus. The length change of the specimen was also measured. Tests of the air-void parameters and distribution of the entrained air were performed. Three specimens (100 mm in diameter) from the same pour of concrete, which was used for the other studies, were prepared to study the air-void system. Reduction was performed as related to air at the rim of the specimen [7].

4. Results

4.1. Salt frost scaling

Fig. 4 shows results of salt frost scaling at 28, 56, and 112 frost cycles. The following conclusions were drawn after 112 cycles:

1. An increased amount of filler did not increase the salt frost scaling.
2. Salt frost scaling was larger in SCC than in NC at the start of testing at 28 days of age, but not at 90 days of age.
3. Salt frost scaling of SCC with 5.5 m hydrostatic pouring pressure did not differ much from that of SCC with small (0.23 m) hydrostatic pouring pressure.
4. SCC with finer limestone powder showed less salt frost scaling than SCC with larger filler.

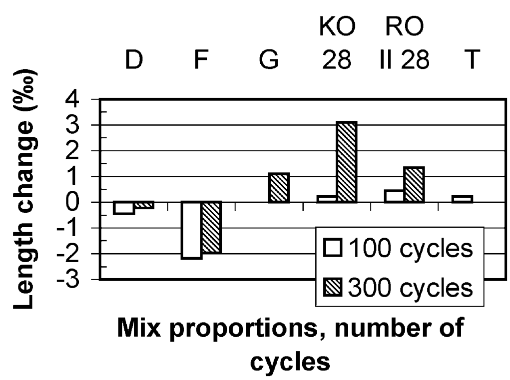

Fig. 6. Change of length after 100 and 300 frost cycles in distilled water. NC and SCC in Table 1.

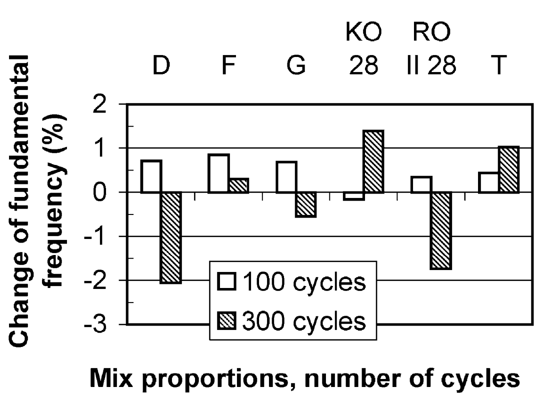

Fig. 5. Change of fundamental frequency after 100 and 300 frost cycles in distilled water. NC and SCC in Table 1.

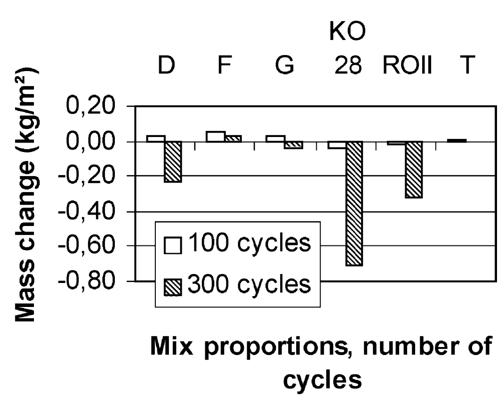

Fig. 7. Change of mass after 100 and 300 frost cycles in distilled water. NC and SCC in Table 1.

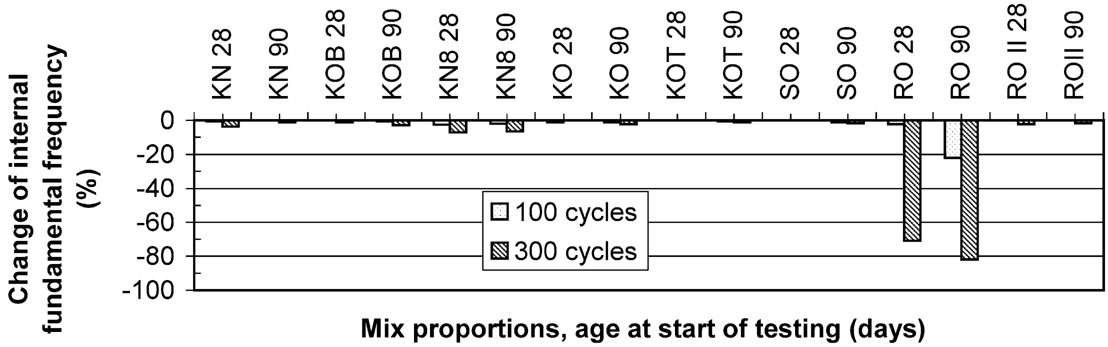

Fig. 8. Change of fundamental frequency (closely related to the elastic modulus) after 100 and 300 frost cycles in distilled water. NC and SCC in Table 3.

4.2. Internal frost resistance

Figs. 5–7 show change of fundamental frequency, length change, and change of mass for concrete shown in Table 1. For the mix proportions D (SCC) and RO (NC), the decrease of fundamental frequency after 300 frost cycles coincided well with the loss of weight. For other SCC, small changes of the measured properties were observed, which indicate that the later SCC performed better in internal frost resistance than concrete D and RO II did (the fundamental frequency may increase due to water absorption). Figs. 8–10 show the change of fundamental frequency, length change, and change, respectively, of mass after 100 and 300 frost cycles for concrete given in Table 3. SCC with limestone filler exhibited much larger changes in fundamental frequency, length, and mass than concrete with silica fume, fly ash, slag, or glass filler, which indicated a lower resistance to internal frost of SCC with limestone powder. NC (RO) was almost destroyed after 300 frost cycles (about 80% loss of fundamental frequency, about 1% increase in length, and about 2.5 kg/m^2 loss of weight). The comparative figures for the second NC (RO II) were 2% loss of fundamental frequency, about 0.1% increase in length, and about 0.3 kg/m^2 loss of weight after 300 cycles. The reason for the large differences of the results on internal frost resistance with the same mix proportion is not known. The mix proportions, the handling, and the measurements of the two NC were identical and these were performed by the

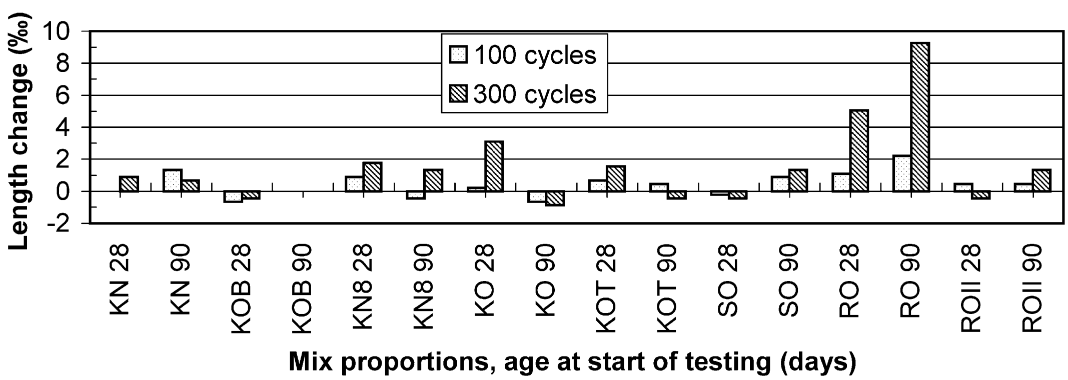

Fig. 9. Length change after 100 and 300 frost cycles in distilled water. NC and SCC in Table 3.

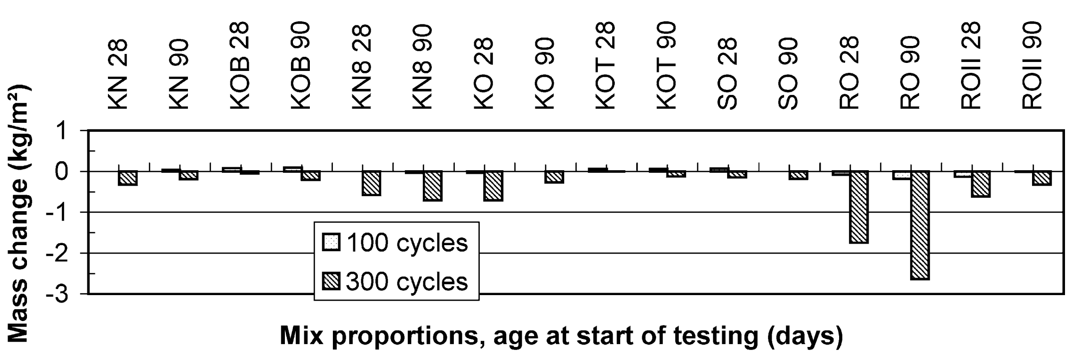

Fig. 10. Change of mass after 100 and 300 frost cycles in distilled water (±20 °C). NC and SCC in Table 3.

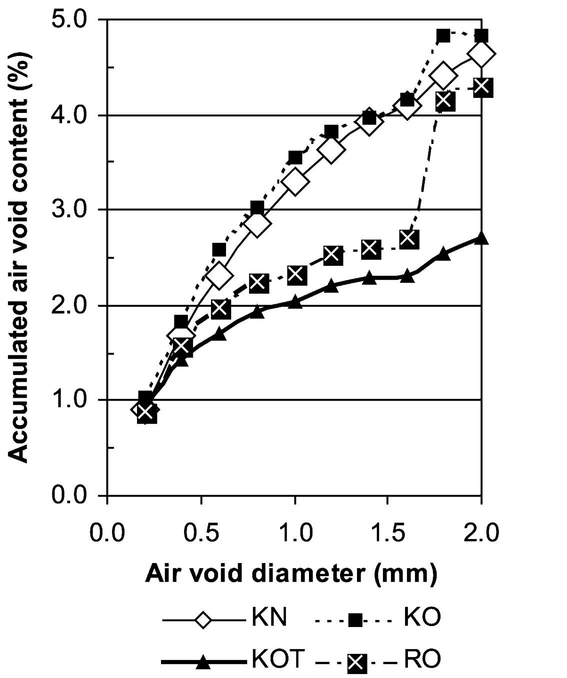

Fig. 11. Accumulated air-void content of concrete given in Table 3 [8].

same laboratory personnel. On average, SCC exhibited much better internal frost resistance than NC. The data on the air-void parameters are of much interest especially with regard to frost resistance. Fig. 11 shows the accumulated air-void content of concrete given in Table 3. Fig. 12 shows the change of fundamental frequency versus air content < 0.5 mm at 300 frost cycles (starting age of 28 days).

5. Discussion

5.1. Salt frost scaling

SCC with ordinary mixing order did not significantly obtain larger salt frost scaling after 112 cycles than NC. However, at a starting age of testing of 28 days, SCC with

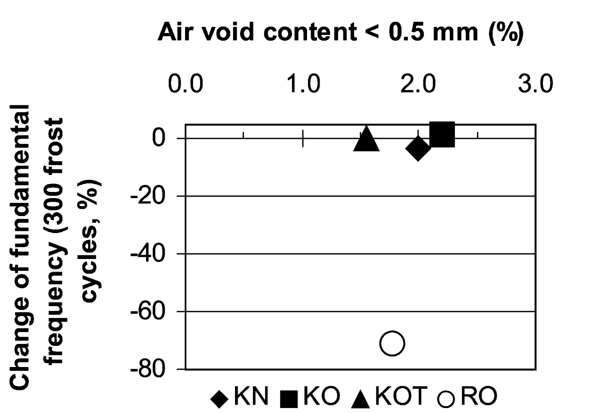

Fig. 12. Change of fundamental frequency versus air content < 0.5 mm. NC and SCC in Table 3. K = SCC; R = NC.

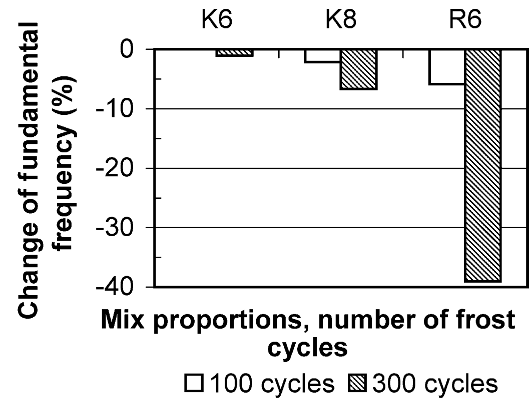

Fig. 13. Average change of fundamental frequency. NC and SCC in Table 3. K = SCC; R = NC; 6 = 6% air content.

ordinary mixing had a tendency to obtain larger salt frost scaling than the NC (RO) with ordinary mixing. At a starting age of testing of 90 days, the opposite was observed. No significant difference was found between salt frost scaling of SCC and NC due to the mixing order. The new order of mixing (filler at last) was supposed to have a substantial effect on the salt frost scaling of SCC [6]. The salt frost scaling should decrease in SCC with filler added at the end of the mixing procedure as compared to the salt frost scaling of SCC with filler added in the beginning of the mixing [6], but this was not seen in the study. Age at start of testing, amount of filler, and air content affected the salt frost scaling. It was observed from Fig. 4 that the salt frost scaling generally decreased at higher age of testing. The air content has a high significance on the salt frost scaling. As expected, increased amount of air resulted in lower salt frost scaling. No significant difference of salt frost scaling was attributed to filler content. Higher fineness of the filler decreased the amount of scaling. Larger pouring pressure did not significantly affect the salt frost scaling of SCC [8].

5.2. Internal frost resistance

SCC exhibited better internal frost resistance than NC. The data on the air-void parameters are of much interest

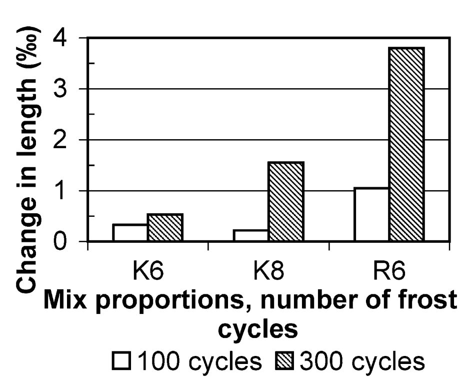

Fig. 14. Average length change. NC and SCC in Table 3. K = SCC; R = NC; 6 = 6% air content.

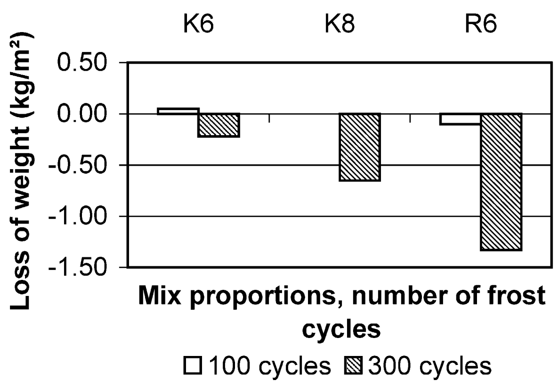

Fig. 15. Summary of the loss of weight. NC and SCC in Table 3. K = SCC; R = NC; 6 = 6% air content.

especially with regard to the frost resistance. Fig. 12, which shows the change of fundamental frequency related to the air content < 0.5 mm at 300 frost cycles, gives no explanation to this phenomenon. More or less the same air-void system was observed in NC and SCC, but the frost resistance differed much. The vibration of the concrete may create pockets around the aggregate where frost damage may occur. This reason for damage is avoided in non-vibrated SCC. Fig. 13 shows the average change of fundamental frequency, Fig. 14 shows the average length change, and Fig. 15 shows the average loss of weight of SCC. The SCC (K6, and K8) in Figs. 13–15 contained the same type of limestone filler combined with 6% or 8% air content. The NC (RO) contained 6% air content. From Figs. 13–15, it was observed that the SCC with 6% air content resisted internal frost better than SCC with 8% air. Increased amount of air content normally increases also the frost resistance. A test of the effect of air entrainment was performed on two SCC (KN and KN8), which showed that the change of fundamental frequency and mass of concrete was significantly larger for SCC with 8% air than for than for SCC with 6% air. Test of significance on the effect of compaction method was performed on three SCC (KO, RO, and RO II) and showed that the change of fundamental frequency and mass of concrete was significantly larger for NC than for SCC.

6. Conclusions

The following conclusions were drawn [8]:

1. No difference was found between salt frost scaling of SCC and NC.
2. Salt frost scaling increased in SCC with blast furnace slag compared with NC without slag.
3. Less salt frost scaling was found for SCC with 12% fly ash and 5% silica fume than for NC without these additives.
4. The mixing order had no influence on the salt frost scaling of SCC.
5. Salt frost scaling for SCC decreased with age at start of testing.
6. The amount of filler did not affect the salt frost scaling of SCC.
7. Pouring pressure up to 5.5 m did not affect the salt frost scaling of SCC.
8. Less salt frost scaling was observed of SCC with limestone powder having higher fineness.
9. SCC exhibited better internal frost resistance than NC.
10. SCC with 6% air content resisted internal frost better than SCC with 8% air.

Acknowledgements

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