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Sulphate resistance of self-compacting concrete

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Abstract

This article outlines a laboratory study on sulphate resistance of self-compacting concrete (SCC). For this purpose, more than 40 cylinders of concrete were subjected to a solution with sodium sulphate, sea or distilled water during 900 days. Age at start of testing was either 28 or 90 days. Weight and internal fundamental frequency (IFF) were measured. Comparison was done with the corresponding properties of vibrated concrete (VC). When cured in a solution with sodium sulphate, the results show larger loss of mass of SCC than that of VC probably due to the limestone filler content in SCC. After curing in water, sea or distilled, no such weight difference between the curing types was observe. IFF did not decrease or differ between the two types of concrete, i.e. no internal deterioration took place due to thaumasite sulphate attack (TSA) during the 900 days of exposure. The project was carried out from 1999 to 2002.

Keywords: Concrete; Durability; Self-compacting; Sulphate; Thaumasite

1. Introduction

1.1. General background

The primary durability properties are chloride ingress, fire resistance, internal frost thaw resistance, salt frost thaw resistance and sulphate resistance for concrete under severe situations. All mentioned properties were recently studied [1]. Salt frost thaw scaling and internal frost thaw resistance did not alter much from the corresponding properties of normal compacting concrete [2]. In the Great Belt tunnel and also in the Channel tunnel, large-scale spalling of the concrete occurred during catastrophic fire owing the low water to cement ratio (w/c) in high-performance concrete (HPC), that was used in these projects. A large amount of filler in self-compacting concrete (SCC) increases the risk of fire spalling as compared to vibrated concrete (VC) due to the low water–powder ratio of SCC corresponding to the low w/c of HPC. Introduction of polypropylene fibers and lowering of the filler content are ways of securing the fire resistance and are thus required in SCC in order to obtain resistance to fire spalling [3]. The chloride ingress in SCC with limestone powder was clearly larger than in VC due to lower cement content in SCC than in VC (the cement was partly replaced by filler) [1,4].

1.2. Mineral additives

SCC contains large amounts of fine particles such as limestone powder, fly ash, silica fume, glass or quartzite filler in order to avoid gravity segregation of larger particles in the fresh mix. Normally, the sum of cement and all filler varies between 450 and 650 kg/m^3 for SCC, i.e. about 200 kg/m^3 more fines than for VC. The fines in SCC prevent the larger aggregate from segregation in the fresh mix due to differences in gravity to the water and the cement in the fresh mix. Large amount of limestone filler in the concrete affects the durability substantially especially chloride ingress and fire resistance even though economical and ecological reasons talk for replacing Portland cement as much as possible by filler [5]. As much as 7% of the industrial fabrication of carbon dioxide, CO_2, is related to the production of cement [5]. One way to reduce the CO_2 release is to use HPC where cement is more efficiently applied, or to replace the cement by filler. However, a large amount of limestone filler increases the carbonation [6] and reduces other durability properties of SCC compared with VC [7]. A protective layer of VC for the steel reinforcement bars may be needed outside the SCC under severe con-

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ditions like at the seaside of Japan [8]. When sulphates are present at a concrete construction with large amounts of limestone powder, there is a substantial risk of thaumasite sulphate attack (TSA) [7]. The reason for this risk is the high specific surface of the limestone powder that causes a solution of CO_2 in the pore water especially at low temperature. TSA may also take place in buried concrete foundations containing limestone aggregate and subjected to an external source of sulphate ions from the surrounding groundwater [9]. After TSA on a concrete, the C-S-H binding in the cement paste converts into a more or less porous mass causing completely deterioration of the concrete [9]. In this case, TSA cannot be prevented by use of sulphate resistant low-alkali cement.

1.3. Objective

The objective of the research was to compare the performance of SCC under influence of a solution of sodium sulphate with the corresponding properties of VC. Measurements of weight and internal fundamental frequency (IFF) were performed. A comparison with the influence of curing in seawater and fresh water on the corresponding properties has been performed.

2. Materials and methods

2.1. Materials

Portland cement and limestone powder were used in the experiments, together with crushed and natural aggregate, superplasticiser (polycarboxylic ether—brand Glenium 51) and an air-entrainment agent (fatty oils—brand Microair).

Table 1
Chemical compositions of the cement

Components	Cement CEM I 42.5 BV/SR/LA (brand Degerhamn)
CaO	65
SiO_2	21.6
Al_2O_3	3.5
Fe_2O_3	4.4
K_2O	0.58
Na_2O	0.05
MgO	0.78
SO_3	2.07
Ignition losses	0.47
CO_2	0.14
Clinker minerals:	
C_2S	21
C_3S	57
C_3A	1.7
C_4AF	13
Water demand (%)	25
Initial setting time (min)	145
Density (kg/m^3)	3214
Specific surface (m^2/kg)	305

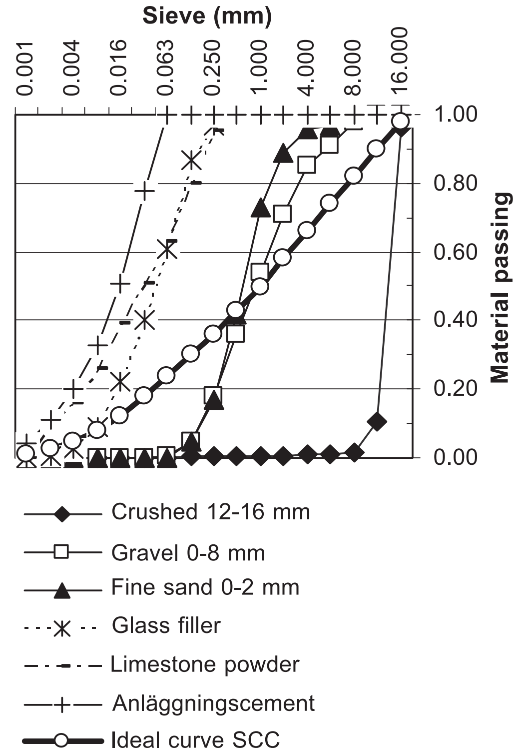

Fig. 1. Grading curve of the materials.

The composition of the cement I42.5BV/SR/LA (brand Degerhamn) is given in Table 1. The mineralogical granulometric properties of the material and the grading of the fresh mix proportions are given in Figs. 1 and 2. The following parameters were studied [1] [Table 2; notations: B = increased amount of filler; K = limestone filler (branch Limus 50); N = new mixing order; O = ordinary mixing

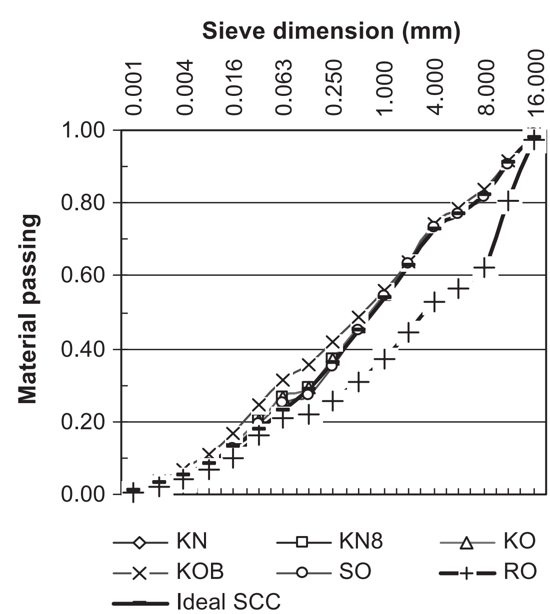

Fig. 2. Grading of solid particles in the fresh mix.

Table 2
Mix proportions and properties of tested concrete (kg/m^3)

Material/mix composition	KN	KOB	KN8	KO	KOT	SO	RO
Crushed aggregate (8–16 mm)	363	371	355	367	363	402	862
Natural sand (0–8 mm)	853	872	836	864	855	786	715
Natural sand (0–2 mm)	316	135	309	320	316	422	146
Limestone filler	183	375	180	186	184	94	0
Cement	418	427	409	423	419	416	431
Air entrainment	585	213	1203	106	117	125	474
Superplasticiser	2.97	4.13	3.2	3.39	3.69	2.99	7.32
Water	163	167	160	165	163	162	168
w/c	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
Slump flow (mm)	720	780	735	620	640	710	110
Flow time until 500 mm (s)	5	7	8	10	8	5	–
Density	2297	2348	2250	2323	2300	2285	2325
Aggregate content (% vol.)	64	65	63	65	65	64	65

B = increased amount of filler; K = limestone filler (branch Limus 50); N = new mixing order; O = ordinary mixing order; R = VC; S = limestone filler (branch Limus 15); T = 5.5 m hydrostatic pouring pressure instead of 0.23 m; II = second; 8 = 8% air content.

order; R = VC; S = limestone filler (brand Limus 15); T = 5.5 m hydrostatic pouring pressure instead of 0.23 m; II = second; 8 = 8% air content]:

1. Compaction type, SCC or VC (O and R)
2. Mixing order, ordinary or new (N and O)
3. Amount of limestone filler (O or B)
4. Type of limestone filler, different in average grading size (O or S)
5. Pouring pressure, 0.25 m, or 6 m (O or T)
6. Air content, 5% or 8% by volume (N or 8)

In total, seven different concretes were studied, six SCC and one VC. From the concrete, larger specimens, 0.23 m in diameter and 0.30 m in length, were prepared, two of each combination. The concrete was sealed cured in a steel container also covered by a steel face. From the large specimen three cylinders, 50 mm in diameter and 150 mm in length, were core drilled both at 28 and 90 days of age. In parallel, 100 mm cubes were cast in order to obtain the strength of the concrete. The cubes were wrapped in aluminum foil in order to be sealed cured. Two types of mixing order of the concrete were used [1,10]:

1. Ordinary mixing order with all dry material mixed with the water for 0.5 min and then with the superplasticiser for another 2.5 min.
2. New reversed mixing order with all material except for limestone powder mixed for 0.5 min and then additional mixing with the filler for 2.5 min.

The grounds for the new reversed mixing order were a better dispersion and frost resistance in a separate investigation of four types of limestone filler for SCC [10]. SCC was not vibrated after casting. VC was vibrated 10 s each time after filling one-third of the steel container.

2.2. Methods

All curing and testing took place at 5 °C. One-third of the specimens were placed in a solution of 18 g/l of sodium sulphate in distilled water, one-third in 1% sodium chloride seawater from Barsebäck, Sweden, and the rest (one-third) of the specimens placed in distilled water. The solutions were renewed once a month. A propeller was placed in the basin in order to secure a good circulation of the solution around the specimens. The method for investigation of the damage has been measurement of surface scaling of material by weighing and IFF. At the start of testing, either at 28 or 90 days of age, at 100, 300 and 900 days of exposure, weights of the specimens and IFF were established [1]. IFF is closely correlated to the elastic modulus of the specimen. A decrease of IFF is a sign of internal deterioration of the concrete, for example, caused by TSA. The precise measurement location for the IFF was marked into the rim of the ends of the cylinders. The cubes were tested for strength at 1, 2, 7, 28 and 90 days.

3. Results and discussion

3.1. Ordinary mixing order

The strength development of the concrete is shown in Fig. 3. The strength development was clearly influenced by

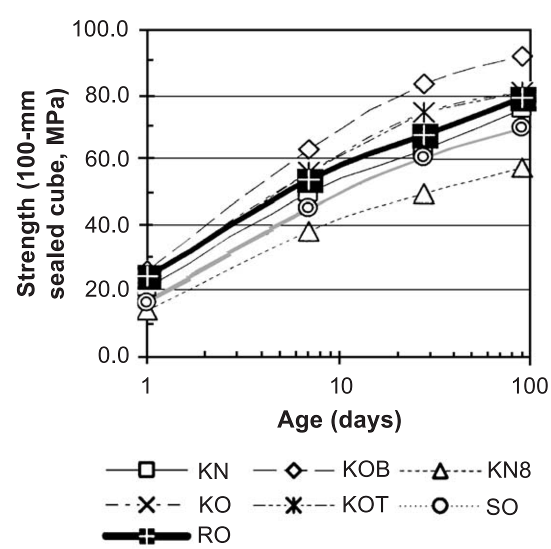

Fig. 3. Strength development of concrete.

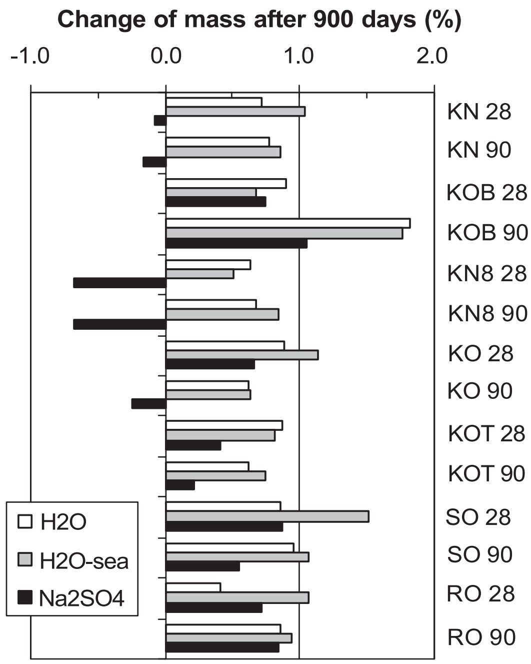

Fig. 4. Change of mass after 900 days of exposure at 5 °C.

the filler mineral additives in the concrete (substantially increased strength) and by the air content (lower strength). A continuous increase of the weight and IFF over 900 days was observed for all concrete types dependent on the way of mixing (ordinary mixing order). The increase of the weight and IFF was independent of type of compaction, SCC or VC, independent of the content of limestone filler, independent of the content of air and independent of the pouring

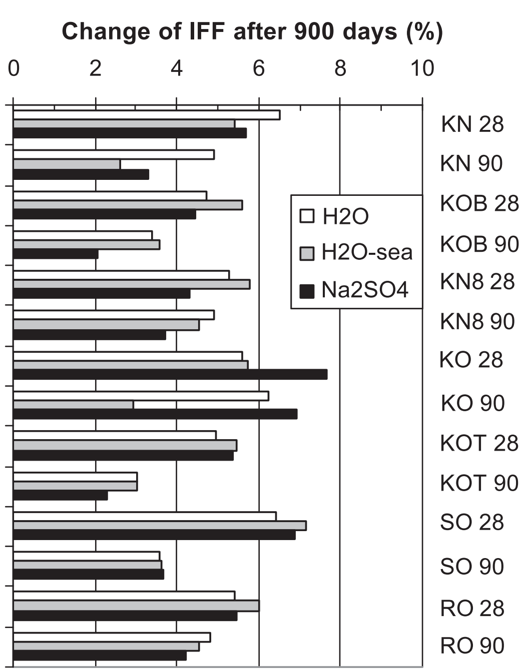

Fig. 5. Change of IFF after 900 days of exposure at 5 °C. IFF = internal fundamental frequency.

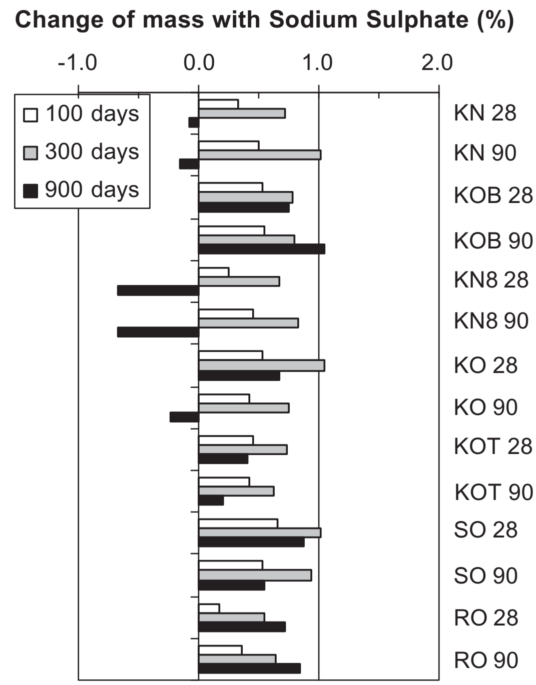

Fig. 6. Change of mass after exposure in of 18 g/l of sodium sulphate and distilled water at 5 °C.

pressure (Figs. 4–8) [1]. Only for concrete KO28 was a decrease of weight observed when curing in sodium sulphate. This decrease was owing to a crack-through the specimen at the rim of the end of it. The general increase of weight and IFF over 900 days was the result of continuous water absorption, slowly compensating for the chemical shrinkage due to the hydration of the cement. The water

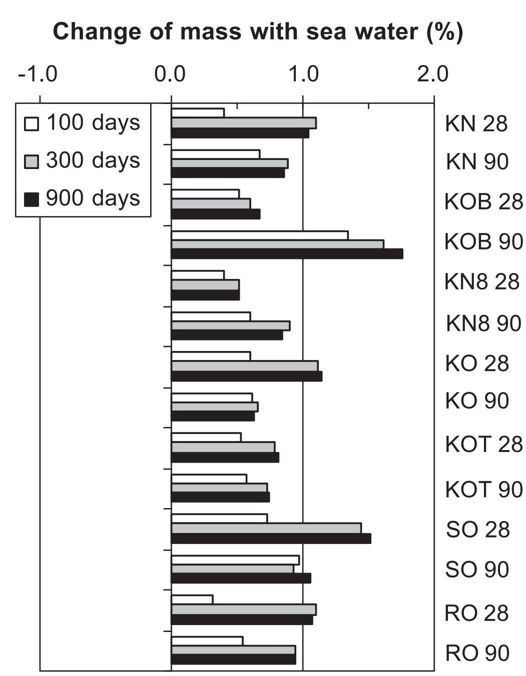

Fig. 7. Change of mass after exposure in seawater at 5 °C.

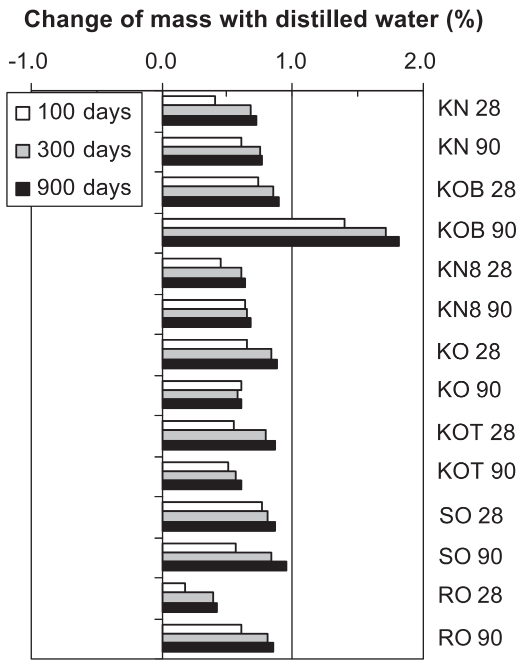

Fig. 8. Change of mass after exposure in distilled water at 5 °C.

absorption did not differ much between SCC and VC at this point. The tests will be continued until significant change may be observed of weight and IFF between the types of concrete studied.

3.2. New mixing order

The grounds for the new reversed mixing order was a better dispersion and frost resistance in a separate investigation of four types of limestone filler for SCC [10]. A significant decrease of weight was observed for SCC with new mixing order exposed to a solution of 18 g/l of sodium sulphate in distilled water. No corresponding decrease as related to IFF of these SCC was observed. The decrease of weight due to a surface scaling attack of the specimen was clearly visible. The specimen performed like it did after a salt frost scaling test [2]. Obviously, limestone filler should be added simultaneously together with cement during the mixing in order to avoid this kind of deterioration of the surface of SCC. Otherwise, when filler is added afterwards, the water is primarily attached to the cement and a proper mixing of cement and limestone filler is prohibited.

3.3. Discussion

The limestone particles are then much more sensitive to sulphate attack than when the particles are mixed with cement and covered by the cement gel. Another effect of curing in sodium sulphate on the weight loss was observed as related to the content of air: larger content of air caused significantly larger loss of weight most probably due to the increased porosity parallel to the increase of air content. At 100 and 300 days of contact the effect of a solution of sodium sulphate on SCC was small but accelerated from 300 until 900 days of experiment (Figs. 4–8). The accelerating effect of a solution of sodium sulphate was only observed in SCC with a large amount of limestone filler combined with a new mixing order and may in turn lead to an interior deterioration. For this reason, the tests will continue. The largest content of sulphates in Swedish groundwater is 1.4 g/l, i.e. the accelerating tests performed in these experiments correspond to 8.7 times larger sulphate concentration than the concentration of sulphate in ground water. Normal requirement at present is a life cycle of 100 years, at least, for bridge concrete. However, the sulphate concentration and the time of exposure are not linear parameters from the experimental point of view. If the content of sulphates in the groundwater is not known, it is still not advisable to use SCC with large amounts of limestone powder together with the new mixing order.

4. Summary and conclusions

After more than 40 extensive tests of sulphate resistance on SCC and VC at low temperatures in parallel, followed by tests of the same concrete cured in sea water or fresh water, the following results were obtained:

1) For concrete with ordinary mixing order, a continuous increase of the weight and IFF over 900 days was observed for all concrete.
2) The increase of the weight and IFF was independent of type of compaction, SCC or VC, independent of the content of limestone filler, independent of the content of air and independent of the pouring pressure.
3) The general increase of weight and IFF for concrete with ordinary mixing was a result of water absorption, slowly compensating for the chemical shrinkage due to the hydration of the cement.
4) A significant decrease of weight was observed for SCC with new mixing order exposed to a solution of sodium sulphate.
5) No corresponding decrease as related to IFF of these SCC was observed for SCC with new mixing order.
6) The decrease of weight for SCC with new mixing order was due to a surface scaling of the specimen.
7) If the content of sulphates in the groundwater is not known, it is not suitable to use SCC with large amounts of limestone powder together with the new mixing order.

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