Comparison of durability parameters of self-compacting concrete and conventional slump concrete designed for marine environment

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ABSTRACT

In this study fly ash concrete, 3-powder concrete (Portland cement, fly ash, silica fume) and concrete based on slag cement have been investigated. Self-compacting and slump concretes were designed using the same aggregate materials and to have as similar compositions as possible. The main differences between the self-compacting concretes and corresponding slump concrete mix compositions were that the self-compacting concretes had a slightly higher paste content, a higher dosage of superplasticizer and maximum aggregate size of 16 mm compared to 22 mm for slump concrete. The compositions of the slump concretes were selected as to meet the typical Danish requirements to concrete structures exposed to marine conditions, i.e. the concrete was air entrained and having a w/c-ratio of 0.40. The concretes were batched and mixed using an industrial scale concrete mixing station applying special procedures that ensured high batching accuracy and identical mixing sequence. The fresh concrete properties of air content, density, slump, slump flow, plastic viscosity and initial setting time were measured and a suite of test specimens were cast comprising cylinders and cubes as well as larger size blocks for long term exposure testing. The strength development and accelerated durability parameters such as frost resistance and chloride migration coefficient were assessed. Chloride penetration profiles were obtained after 6 months of exposure to sea water. The results indicate that self-compacting concrete performs similar to the conventional slump concrete in all aspects of durability.

Key words: Self-compacting concrete, slump concrete, supplementary cementitious materials, durability.

1. INTRODUCTION

Self-consolidating concrete (SCC) is widely used in DK. The majority of precast plastic concrete is SCC and close to 40 % of the ready-mixed concrete production is SCC. However, even if SCC in Danish regulations is fully allowed for any exposure, SCC is generally not used under severe exposure conditions such as marine environments, the purpose for which it was originally developed in Japan in the late 1980's [1].

One reason for the limited use of SCC might be a lack of economic benefit. It is easy for the contractor to see the benefit from needing only two people to do the job that with conventional concrete would require six people. This is typically the case for simple slabs on ground when comparing the required manpower of a SCC solution compared to a slump concrete solution, and therefore the extra cost per cubic meter of SCC pays off [2]. For the more complicated and perhaps vertical formwork often required for structures exposed to severe environmental conditions the picture can be less evident. The benefit of using SCC may be reduced for a number of reasons:

- the labor cost for the actual casting process is relatively low
- the cost of formwork is increased as hydrostatic pressure needs to be accounted for
- the need for more careful control of concrete workability
- the need for more careful planning and control of the concrete casting
- the geometrical accuracy of free surfaces is not as good as can be achieved with slump concrete.

However it must be realized, that even if SCC is allowed in any exposure class only limited documentation exists that SCC based on local materials and traditions will perform just as good in service in terms of durability as a conventional solution using slump concrete. This is obviously not an optimal situation for the promotion of SCC.

Consequently, in Denmark there is a need for documentation of durability properties of SCC mix designs having comparable materials cost to conventional concrete mix designs. This was among the reasons why Femern A/S as owner of the coming Fehmern Belt Fixed Link between Denmark and Germany initiated laboratory and field tests on the durability of a variety of concrete compositions - including SCC - all potentially suitable for marine structures. Selected durability parameters from accelerated testing as well as parameters from large marine exposure test specimens are presented and compared for SCC and conventional slump concrete with three different binder systems Portland cement (CEM I) + fly ash, Portland cement (CEM I) + fly ash + silica fume, and blast furnace slag cement (CEM III/B).

2. EXPERIMENTIAL WORK

The concrete compositions and the testing program were designed in a co-operation between Femern A/S and Danish Technological Institute. The experimental work comprised mixing, casting and testing of six types of concrete, three self-compacting and three conventional slump concretes of similar binder compositions; Portland cement (CEM I) + fly ash, Portland cement (CEM I) + fly ash + silica fume, blast furnace slag cement (CEM III/B). For each concrete type two concrete blocks with dimensions 2000 x 1000 x 200 mm and 1000 x 1000 x 200 mm respectively were produced and furthermore a number of cylinders and cubes were cast. The large blocks were exposed to the marine conditions at the Fehmern Belt exposure site at Rødbyhavn, while the smaller block, the cylinders and the cubes were used for initial characterization of the different concrete types.

The test program comprised the measurement of fresh concrete properties (air content, density, slump/slump flow, air void distribution, setting time, bleeding and for SCC furthermore yield stress, plastic viscosity and t_{500}) on each batch of concrete. The cylinders were used for determination of compressive and splitting tensile strength developments (EN 12390-3, EN 12390-6, EN 12390-7) and the cubes were used for determination of frost resistance according to SS 13 72 44-IA. Cores were drilled from the smaller elements after 28 maturity days and used for determination of compressive strength (EN 12504-1) and frost resistance (SS 13 72 44-IIIA), air void analysis (EN 480-11), petrographic analysis (DS 423.41, DS 423.42, DS 423.43, DS 423.44, DS 423.45) and measurement of chloride migration coefficient after 28 as well as 180 maturity days according to NT Build 492.

Cores were drilled from the large elements after 6 months of exposure and used for determination of compressive strength (EN 12504-1), air void analysis (EN 480-11), petrographic analysis (DS 423.41, DS 423.42, DS 423.43, DS 423.44, DS 423.45) and measurement of chloride profiles from 1m below the water level according to the principles of NT Build 443. Based on the chloride profiles the diffusion coefficient and surface concentration was estimated.

Only selected important durability related parameters from the test program are presented in this article. More data on the six concrete types presented in this study as well as nine other concrete types can be found at www.concreteexpertcentre.dk.

2.1 Materials and mix proportions

The cementitious materials used were a CEM I 42.5 N Portland cement (low alkali sulfate resisting cement) from Aalborg Portland, class F fly ash (Emineral B4) from the coal-fired power plant in Asnæs, silica fume from Elkem in aqueous suspension (EMSAC 500S) and a CEM III/B 42.5 N slag cement from CEMEX’s plant in Schwelgern Germany.

The fine aggregate used was Storebæltssand 0/2 mm obtained by sea dredging at “Rønne Banke” near the Danish island of Bornholm in the Baltic Sea. The Storebæltssand was used back in the early 1990’s for the production of the tunnel lining elements for the Great Belt Link. The fine aggregate does primarily consist of quartz.

The coarse aggregate used was crushed granite from Rønne on the Danish island of Bornholm in the fractions 4/8, 8/16 and 16/22 mm. The Rønne granite has a long track record in Danish infrastructure projects and was e.g. used for the concrete for the East Bridge of the Great Belt Link.

Air entraining agent (Amex SB 22) and superplasticizer (Glenium SKY 532-SU) from BASF were used. In order to simultaneously meet the requirements to air content (3-5 %) and air void distribution (spacing factor below 0.2 mm) additional defoamer had to be added to the superplasticizer to minimize its entrainment of relatively large air voids.

The slump concretes were proportioned to meet the typical Danish requirements to concrete structures exposed to marine conditions, i.e. the concretes were air entrained with a target air content of 4.5 % and having a w/c-ratio of 0.40. The w/c-ratio was calculated using activity factor of 2 for silica fume and 0.5 for fly ash according to the Danish concrete standard DS 2426. The self-compacting concretes were proportioned based on the slump concretes, but with slightly higher paste content. Furthermore the maximum aggregate size was reduced from 22 mm for the slump concretes to 16 mm for the self-compacting concretes. Target slump for the slump concretes was 160 mm and target slump flow for the self-compacting concretes was 580 mm. The mix proportions of the six types of concrete are presented (without admixture content) in Table 1.

2.2 Mixing, casting and curing of concrete

The mixing of the concretes was performed in an industrial 375 liter counter-current panmixer with a capacity of 250 liter ready mixed concrete. The mixing station was equipped with 5 aggregate silos and 4 powder silos. The use of an industrial mixing station ensures the applicability of the results to actual full scale concrete production. In order for the concretes to be produced with precisely the desired water/cement ratio (within ± 0.002 of the target 0.400), a special batching procedure was adopted, involving very accurate determination of moisture content of the aggregates. Each aggregate was weighed separately onto the conveyor belt, and samples were taken for determination of moisture content using microwave ovens, before the aggregate was transferred to the mixer. After determination of moisture content, the appropriate amount of water to be added to obtain a water/cement ratio of 0.400 was calculated and subsequently weighed into the mixing stations water tank. The mixer, already containing the aggregates, was started and the powder was added followed by water, air entraining agent and finally superplasticizer. The superplasticizer was added with a delay of 30 seconds from the addition of water and the final mixing time after dosage of all materials was 120 seconds. After mixing, the concrete was discharged to a 500 liter crane bucket and fresh concrete properties were determined.

For the casting of cylinders/cubes and the small concrete blocks, batches of 230 liter concrete were produced. The cylinders/cubes were cast using a vibration table for the slump concretes, while no compaction was applied for the self-compacting concretes. For the casting of the larger concrete blocks, two batches of 230 liter concrete were produced. The blocks were cast from the crane bucket into the formwork. The slump concretes were cast in 3 and 6 layers of 30-40 cm for the small and large blocks respectively and each layer was compacted using a Ø40 mm poker vibrator according to HETEK report no. 74 [3]. The self-compacting concretes were cast through an Ø100 mm fire hose mounted at the bottom of the crane bucket using a casting rate of approximately 20 meters per hour.

Table 1 — Composition and fresh concrete properties of the six concrete types tested.

Concrete ID			Fly ash	Fly ash SCC	3-powder	3-powder SCC	Slag ce-ment	Slag ce-ment SCC
Powder composi-tion	Portland cement	%-wt	75	75	84	84		
	Slag cement	%-wt					100	100
	Fly ash	%-wt	25	25	12	12		
	Silica fume, solid	%-wt			4	4		
Concrete composition	Portland Cement	kg/m³	300	336	300	350	360	410
	Fly ash	kg/m³	100	112	43	50	-	-
	Silica fume, solid	kg/m³	-	-	14	17	-	-
	Water content	l/m³	140	157	140	163	144	164
	Aggregate 0/2	kg/m³	642	678	677	687	689	686
	Aggregate 4/8	kg/m³	367	349	377	354	373	353
	Aggregate 8/16	kg/m³	271	704	272	713	263	712
	Aggregate 16/22	kg/m³	541	-	543	-	525	-
Cylinders and cubes	Slump	mm	160	-	160	-	140	-
	Slump flow	mm	-	570	-	540	-	580
	t_{500}	s	-	4.5	-	6.0	-	3.5
	Yield stress	Pa	-	51	-	63	-	45
	Plastic viscosity	Pa·s	-	58	-	47	-	62
	Density	kg/m³	2340	2350	2380	2340	2360	2310
	Setting time,	hr:min	04:50	05:10	05:00	06:20	05:40	08:20
	Air content	%	5.4	4.2	4.9	4.3	4.4	5.2
Small block	Slump	mm	180		180	-	160	-
	Slump flow	mm	-	570	-	550	-	560
	t_{500}	s	-	5.0	-	4.5	-	4.5
	Yield stress	Pa	-	49	-	60	-	53
	Plastic viscosity	Pa·s	-	70	-	55	-	59
	Density	kg/m³	2340	2390	2360	2349	2360	2340
	Setting time,	hr:min	-	-	-	-	-	-
	Air content	%	5.3	3.2	5.4	4.0	4.0	4.4
	Spacing factor	mm	0.12	0.24	0.15	0.18	0.19	0.15
Large block	Slump	mm	110	-	140	-	160	-
	Slump flow	mm	-	620	-	590	-	610
	t_{500}	s	-	5.0	-	3.5	-	3
	Yield stress	Pa	-	34	-	41	-	35
	Plastic viscosity	Pa·s	-	91	-	38	-	59
	Density	kg/m³	2330	2360	2350	2370	2320	320
	Setting time,	hr:min	-	-	-	-	-	-
	Air content	%	5.5	4.3	5.2	3.5	4.8	4.8

Demolding of the cylinders/cubes and concrete blocks was carried out 24 hours after casting. The cylinders/cubes were placed in a 20 °C water curing tank until test, while the blocks were wrapped in plastic and placed indoors until a maturity of at least 14 days was reached for the larger elements and 28 days for the smaller elements. Thermocouples cast into the blocks were used to monitor the maturity. In early April 2010 the large concrete blocks were placed at the exposure site in Rødbyhavn when they had reached a maturity of approximately 45 days (43-49 days).

3. RESULTS AND DISCUSSION

3.1 Compressive strength development

The compressive strength developments of the six different concrete types are presented in Table 2 and Figure 1. Each data point represents the average of two measurements on Ø150 mm cylinders.

The strength development of SCC and slump concrete are similar for concrete with corresponding binder systems. The 3-powder concretes and slag cement based concretes have very similar compressive strengths at all maturities. For the fly ash concretes the rate of strength development is the same for SCC and slump concrete, however, the SCC consistently exhibit roughly 10-20 % higher strength at all maturities than the slump concrete. This difference cannot readily be explained even with the 1.2 % lower air content of the fly ash SCC.

Table 2 ─ Compressive strength development (Ø150 mm cylinders) of the six different concrete types tested.

Fly ash		Fly ash SCC		3-powder		3-powder SCC		Slag cement		Slag cement SCC	
Maturity (hours)	Strength (MPa)	Maturity (hours)	Strength (MPa)	Maturity (hours)	Strength (MPa)	Maturity (hours)	Strength (MPa)	Maturity (hours)	Strength (MPa)	Maturity (hours)	Strength (MPa)
13.4	4.5	16.1	7.5	13.2	5.3	15.7	6.8	15.8	1.9	20.8	2.3
25.4	10.9	25.6	12.8	26.4	14.7	22.1	10.1	23.1	3.6	27.9	3.6
48.8	17.6	48.5	21.1	48.6	20.1	45.9	19.0	41.1	11.2	51.2	13.7
76.2	22.1	72.1	26.1	75.4	25.5	69.6	23.4	62.5	17.6	75.9	22.6
168	29.7	168	36.8	168	35.4	168	37.6	168	36.0	168	38.9
672	43.8	672	52.7	672	56.2	672	59.5	672	55.6	672	52.9
1344	50.8	1344	55.4	1344	61.3	1344	61.5	1344	59.8	1344	59.0
Air, fresh (%)	5.4		4.2		4.9		4.3		4.4		5.2

3.2 Frost resistance and air void analysis

The results from testing of frost resistance of the different concretes are presented in Figures 2 and 3 for cast cubes and drilled cores from the small blocks respectively.

For the cast cubes the frost resistance of slump concrete and SCC are virtually identical. The fly ash and 3-powder concretes have "very good" frost resistance (< 0.10 kg/m^2 scaling after 56 freeze/thaw cycles), while both the CEM III/B concretes have only what corresponds to "good" frost resistance according to the SS 13 72 44 test method. The finding that concrete containing blast furnace slag has a reduced salt scaling frost resistance is in agreement with previously reported results [4], [5].

The results for the drilled cores again characterize the CEM III/B concretes as having as a "good" frost resistance. For the fly ash concretes the SCC exhibits significantly poorer frost resistance, "acceptable" as compared to "very good", than the slump concrete, while the opposite trend although less pronounced is the case for 3-powder binder system. For the fly ash concretes, the observed difference might be explained by a low air content (2.8 %) and high spacing factor (0.24) in the hardened SCC compared to the slump concrete (see Table 2). Generally, the spacing factor should be below 0.2 to achieve good frost resistance. The air void analysis can however not explain why the 3-powder SCC concrete has a better frost resistance compared to the slump concrete.

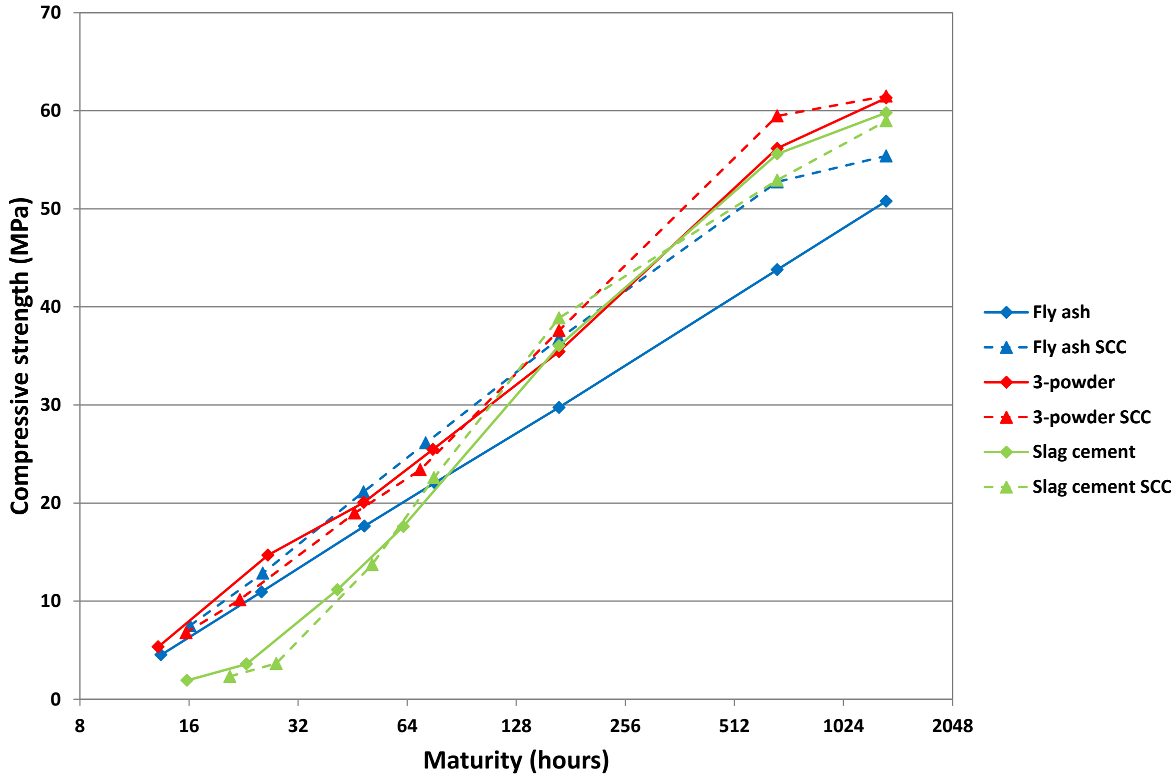

Figure 1 — Compressive strength development (Ø150 mm cylinders) of the six different concrete types tested.

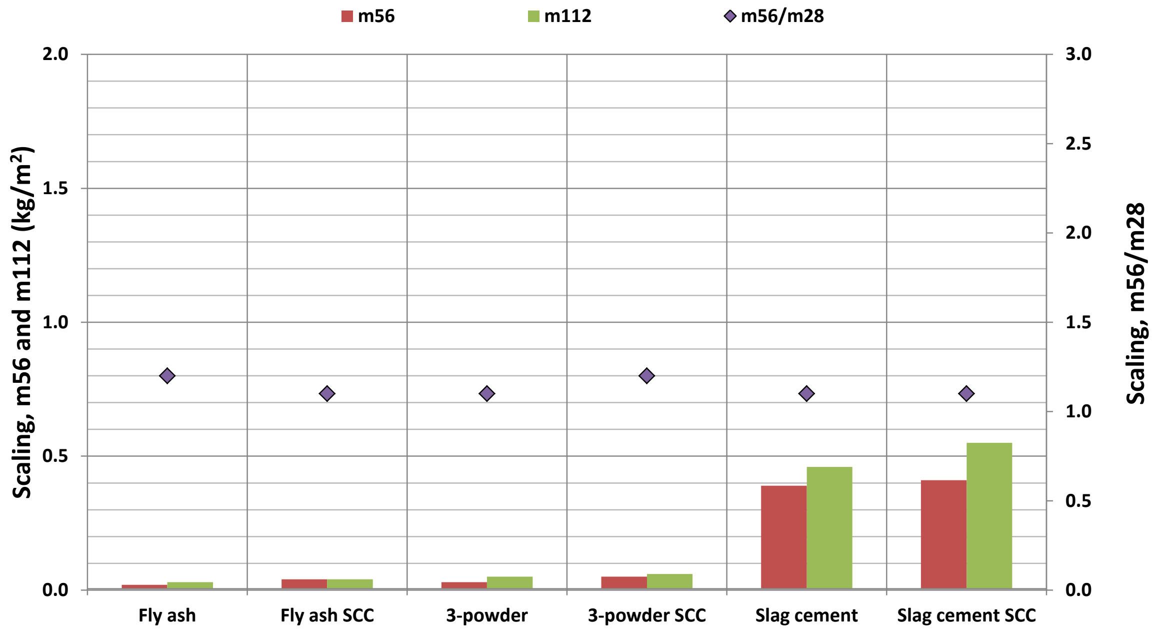

Figure 2 — Frost resistance of cast cubes representing the six different concrete types tested.

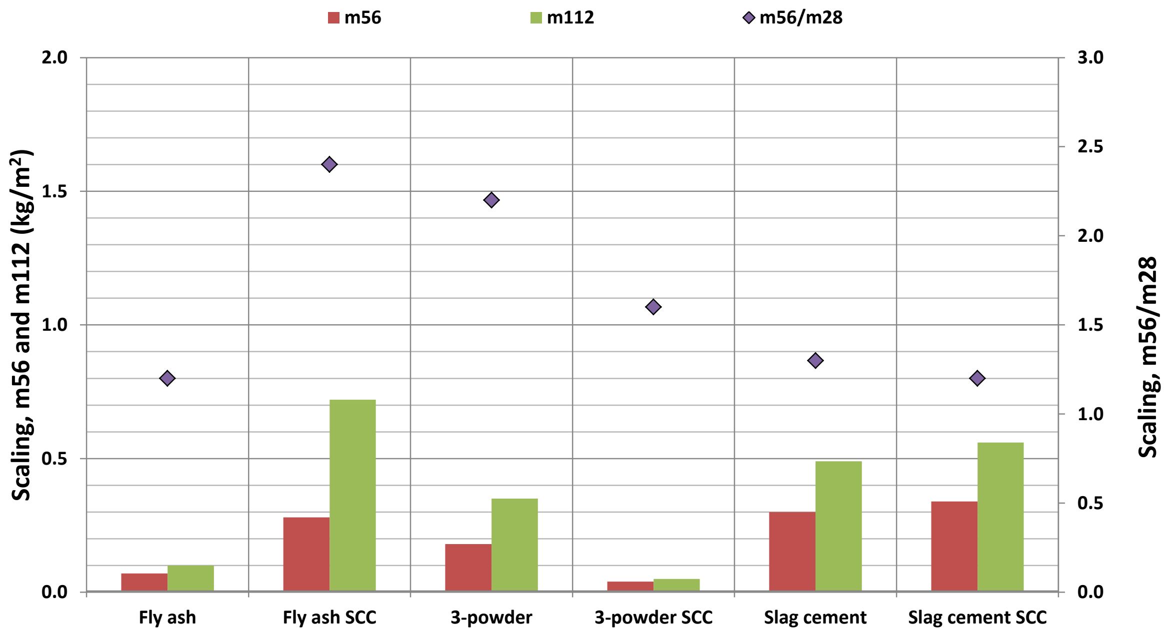

Figure 3 — Frost resistance of drilled cores taken from the small blocks.

In general the results seem to suggest that there is no difference in the frost resistance between slump concrete and SCC of comparable air void structure provided that both types of concrete have been cast properly. Although not supported by any referenced results this was also the conclusion by the recent RILEM TC 205-DSC [6].

3.3 Chloride ingress

The results from testing of chloride ingress parameters are presented in Table 3. The measured NT Build 492 migration coefficients from drilled cores taken from the small block are also presented graphically in Figure 4, whereas the obtained chloride profiles after 180 days of exposure to sea water at Fehmern Belt exposure site at Rødbyhavn are shown in Figure 5.

Table 3 — Chloride ingress parameters measured for the six different concrete types.

Concrete type	NT Build 492, 28 days	NT Build 492, 180 days	Chloride ingress profiles, 6 month exposure		
	Migration coefficient ($x10^{-12}$ m^2/s)	Migration coefficient ($x10^{-12}$ m^2/s)	Diffusion coefficient ($x10^{-12}$ m^2/s)	C_S (%-wt)	K (mm/(years)$^{0.5}$)
Fly ash	27.5	2.3	2.93	0.35	19.9
Fly ash SCC	23.3	2.9	3.11	0.40	21.6
3-powder	9.7	2.8	2.76	0.44	20.9
3-powder SCC	9.9	3.1	1.68	0.46	16.6
Slag cement	2.5	1.3	0.61	0.29	8.5
Slag cement SCC	2.3	1.0	0.33	0.31	6.4

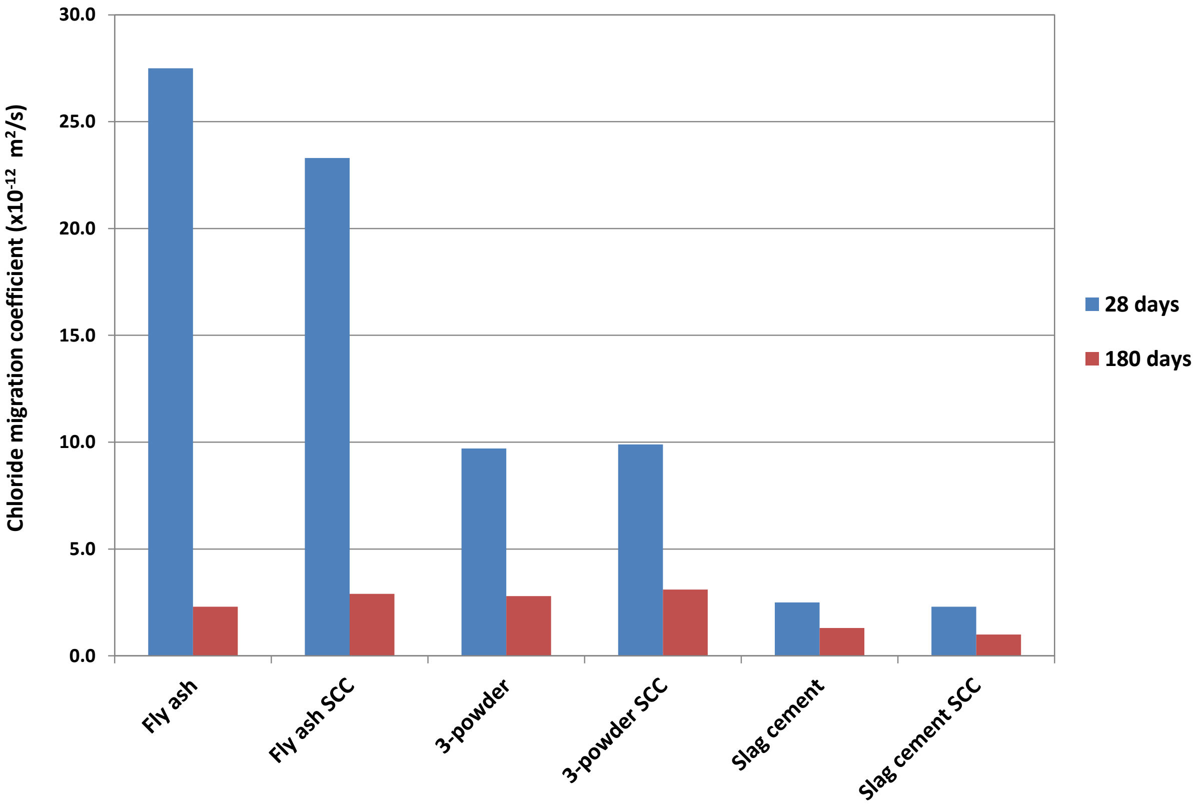

Figure 4 — Chloride migration coefficients of drilled cores taken from the small blocks.

No difference between slump concrete and SCC could be recognized in the chloride ingress parameters recorded.

Quite similar chloride migration coefficients were obtained for the respective slump and SCC concretes with same binder systems at 28 maturity days as well as after 180 maturity days. The development in the migration coefficient over time is markedly different for the three binder systems investigated. At early stages (28 days) as expected the slag cement concretes have the lowest values, the 3-powder concretes have intermediate values, and the fly ash concretes the higher values. After 180 days the slag concretes still exhibit the lowest migration coefficients, but the fly ash concretes have "caught up" with the 3-powder mixtures; both binder systems having migration coefficients in the range 2 to 3 $x10^{-12}$ m^2/s or about twice that of the slag cement concretes.

The chloride profiles of cores drilled below sea level from the larger blocks after six months of exposure are presented in Figure 5. As seen from the figure the ingress profiles of the SCC and slump concretes with similar binder systems are fairly similar. These similarities are also expressed in the diffusion coefficients, surface concentrations and K value parameters estimated from the best fit Fick's second law solution to the profiles (Table 3). For the 3-powder and slag cement concretes, the SCCs generally have lower chloride contents at all depths than their slump counter parts, whereas the opposite is the case for the fly ash concretes. However, the differences are quite small and presumably within what can be expected between two profiles from the same level of the same concrete specimen.

Only limited information has until now been made available in the literature concerning chloride ingress in SCC [6]. However, a recent Swiss study [7] investigating the chloride ingress into concrete by three different accelerated methods of four different binder systems at different water/powder ratios ranging from 0.35 to 0.60 supports the findings of the current study, i.e. that the chloride resistance of SCC is similar to that of slump concrete with corresponding binder.

Likewise, Zhu and Bartos [8] found that the chloride migration coefficients of fly ash SCC and fly ash slump concrete with water to powder ratios of 0.35 and 0.36 respectively were almost identical, i.e. 6.3 and 6.6 x 10^{-12} m^2/s.

A discussion of the reasons behind the observed differences between the chloride ingress parameters of the three investigated binder systems is beyond the scope of this paper.

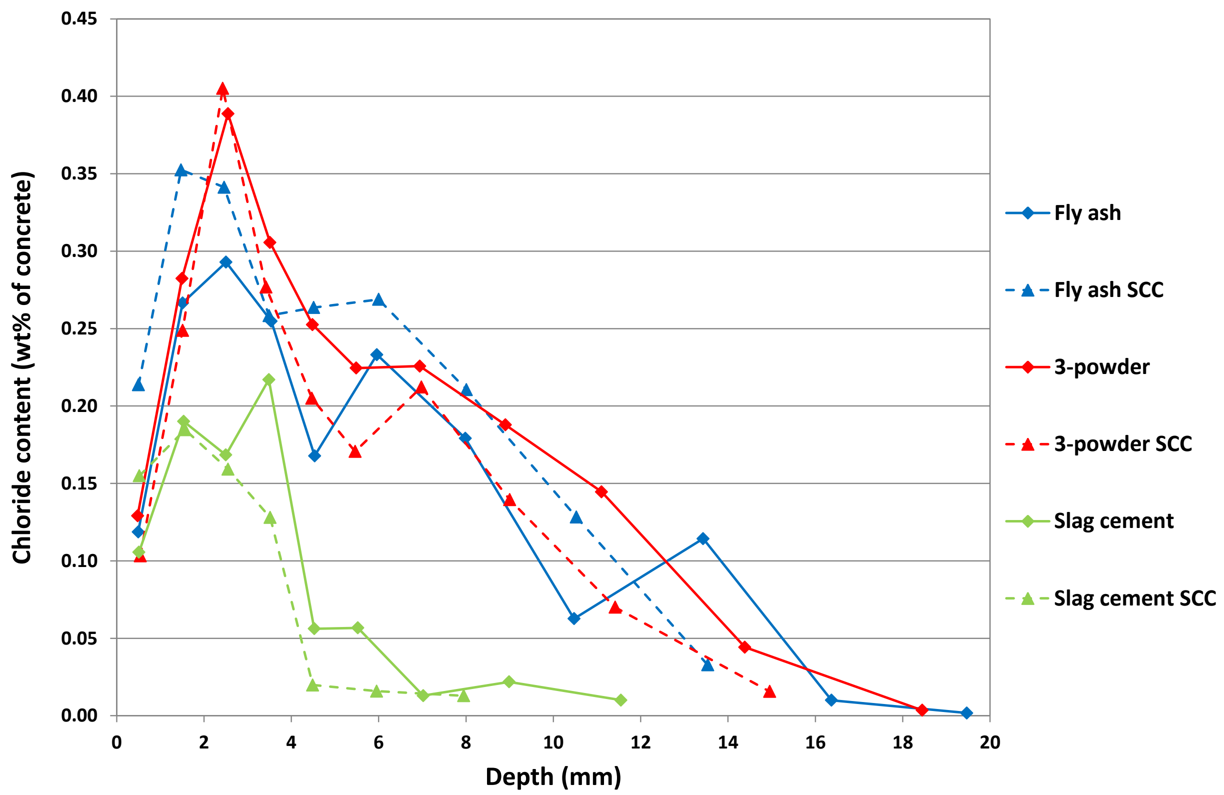

Figure 5 — Chloride profiles from 1m below the waterline after 6 months exposure of large blocks at the Fehmern Belt exposure site at Rødbyhavn.

4. CONCLUSIONS

For the three investigated binder systems Portland cement (CEM I) + fly ash, Portland cement (CEM I) + fly ash + silica fume and slag cement (CEM III/B) it may be concluded that self-compacting concrete performs similar to conventional slump concrete with respect to the durability parameters investigated.

The following sub-conclusions can be drawn:

1) The compressive strength development up to 56 days of maturity when stored immersed in water are very similar.

2) The frost resistance of slump and SCC concrete is similar provided that the air void structure of the concretes is fairly similar. The investigated fly ash and 3-powder concretes had good frost resistance, whereas the slag cement based concretes exhibited somewhat more scaling than the two other binder systems.

3) The slump and SCC concretes have very similar chloride migration coefficient after both 28 and 180 days. The slag cement concretes have the lowest chloride migration coefficients at both ages, while the fly ash concretes have the far largest reduction in migration coefficient from 28 to 180 maturity days.

4) The chloride profiles are similar for the respective slump and SCC concretes after 6 months of exposure with some minor fluctuations. As a direct result of the profile similarities the estimated parameters (diffusion coefficient, surface concentration and K value) of the Fick's second law solutions to the recorded profiles reveal no differences between SCC and slump concrete.

The above conclusions are valid for well-proportioned concrete that has been correctly batch, mixed, cast and cured into a concrete body of homogeneous character. For such concrete it seems, perhaps not surprising, evident that the durability is governed by the binder composition, while the workability of the concrete in the fresh state has no influence.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge Femern A/S and the Danish Expert Centre for Infrastructure Construction, without their support this paper would not have been possible.

REFERENCES

1. Okamura, H.; and Ouchi, M., "Self-Compacting Concrete," *Journal of Advanced Concrete Technology*, V. 1, No. 1, Apr. 2003, pp. 5-15.

2. Poulsen, Aage, "Cost savings by use of SCC in floors," *Nordic SCC Net Workshop, Copenhagen*, 19 June, 2006. (Powerpoint presentation at http://www.scc-konsortiet.dk/12180).

3. Vejdirektoratet, "Stavvibrering, Højkvalitetsbeton, Entreprenørens teknologi - nvisning," *HETEK rapport 74*, 1997, pp. 31, in Danish. (http://www.hetek.teknologisk.dk/16228).

4. Utgenannt, P., "Frost resistance of concrete – Experience from three field exposure sites," *SP report 2001:30*, Swedish National Testing Institute, Borås, Sweden, 2001.

5. Valenza II, J.J.; and Scherer, G.W., "A review of salt scaling: I. Phenomenology," *Cement and Concrete Research*, V. 37, 2007, pp. 1007-1019.

6. RILEM Technical Committee 205-DSC, "Durability of self-compacting concrete", *Materials and Structures*, V. 41, 2008, pp. 225-233.

7. Loser, R.; Lothenbach, B.; Leeman, A.; and Tuchschmid, M., "Chloride resistance of concrete and its binding capacity – Comparison between experimental results and thermodynamic modeling," *Cement and Concrete Composites*, V. 32, 2010, pp. 34-42.

8. Zhu, W.; and Bartos, P.J.M, "Permeation properties of self-compacting concrete," *Cement and Concrete Research*, V. 33, 2003, pp. 921-926.