SELF-CONSOLIDATING CONCRETE, SCC, FOR SUBMERGED REPAIR OF WATER POWER DAMS AND HARBOURS

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Abstract
This article emphasis a description of experimental and analytical studies of workability, freezing and thawing resistance and internal frost resistance of SCC with different water-binder ratio, w/b and increased amount of air content. A comparison was done between the corresponding properties of normal concrete, NC, cast submerged, both concrete types intended for submerged repair of dams, foundations and columns. Twelve SCC with \( w/b = 0.35, 0.40 \text{ or } 0.45 \) and 12 NC with \( w/b \) varying between 0.45 and 0.78 were studied. The air content of NC varied between 1 and 11% vol. The strength development was followed in parallel. The tests were carried out in fresh water or in water with 3% of sodium chloride. The temperature during testing varied between +/- 20 °C, twice a day. The results indicate that SCC with \( w/b = 0.40 \) and 7.5% silica fume may be used for submerged repair without adding Viscosity Modifying Agents, VMA. Recommendations are presented for mix proportions of SCC intended for submerged concrete repair.

1. Introduction, limitations and objective

1.1 Introduction
SCC 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 internationally and in Sweden. Nineteen full-scale bridges and other full-scale projects now exist from SCC in Sweden [1]. The technique has also been introduced for dwelling houses, tunnels and office buildings [2-4]. SCC has been introduced for the production of poles, piles and pillars [5-8]. Regarding concrete under severe circumstances for construction of bridges, dams, tunnels and so forth, the requirements of durability are higher and a higher level of documentation is required than for concrete that is used for dwelling houses or office buildings. The primary durability properties are chloride ingress, fire resistance, internal freezing and thawing resistance, salt freezing and thawing scaling and sulphate resistance for concrete under severe situations. All mentioned properties of a typical construction concrete were studied at Lund University. Salt freezing and thawing scaling, internal freezing and thawing resistance and sulphate resistance did not differ much from the corresponding properties of NC. Chloride ingress was larger in SCC than in NC. It is known from the Great Bält railway tunnel and also from the Channel railway tunnel that large scale fire spalling of the concrete may occur especially in concrete at low \( w/b \). Such scaling is avoided by including polypropylene fibre also in SCC or by avoiding large quantities of filler in SCC, i.e. by the use of a cement-powder ratio, c/p, high enough. \( w/b \), high enough, was also important for avoiding fire spalling [9-12].
1.2 Limitations
Twelve SCC with w/b = 0.35, 0.40 or 0.45 and 12 NC with w/b varying between 0.45 and 0.70 were studied related to strength and freezing and thawing resistance. About 3 months age applied at the start of testing. The tests were carried out in fresh water (internal frost resistance) or in water with 3% of sodium chloride (salt frost scaling). The temperature during testing varied between +/- 20 °C, twice a day. The concrete was water-cured from casting until testing. All the specimens were core-drilled from a larger specimen of concrete. In this way the effects of bleeding, carbonation, concrete skin, crazing, segregation and so forth were avoided. The strength development was followed in parallel.

1.3 Objectives
The objectives were to investigate freezing and thawing resistance (internal frost resistance and salt frost scaling) of submerged cast SCC at different w/b and different air content intended for repair of concrete for water power plant dams and harbours in severe conditions. The objective was also to compare the result with the corresponding properties of normal submerged cast concrete, NC. Finally the objective was to give recommendations for mix proportions of SCC for repair of water power plant dams and harbours durable to freezing and thawing attack.

2. Previous research

2.1 General
The advantage by use of submerged cast concrete compared with NC is to avoid a dry keeping barrier around the construction during the production at site [13]. Submerged cast concrete is used by the Swedish Road Administration primary for foundation of bridges in rivers and at repair of these constructions [14]. Substantial damages have been observed at the upstream side of uninsulated dams of concrete water power plant. In this positions repair is necessary. In order to resist penetration of water in the fresh state anti-washing out compound are necessary to add to a concrete that is cast submerged by a pump hose. In Sweden cellulose based anti-washing out compound is used but abroad mostly polymer based anti-washing out compounds (branch mark: Wellan gum). When using these compounds it seems to result in low frost resistance. Both the Swedish Road Administration and the water power plants require a repair concrete to be durable to frost. To be cast submerged the process and the level of the concrete is checked by divers and afterwards by visual inspection and by strength tests of drilled cores. In advance of the pumping the slump (flow) of the concrete is tested. Pre-testing of the concrete also may take place of frost resistance and strength as for a construction concrete. The w/b of a NC for foundation of bridges in rivers and at dams of concrete water power plants normally is high (around w/b = 0.50) which is an disadvantage as concerns frost resistance. Even though the repair concrete will be frost resistant the existing construction may deteriorate when subjected to further frost attack. In order to prevent frost water power dams may be insulated but bridge foundations not. All damaged concrete at bridge foundation must be carefully cleaned and the lose part and parts damaged by frost removed before casting a new face of the structure. Probably the repair concrete may not be used in sea or brackish water since chlorides then may be mixed into the fresh concrete.

2.2 Requirements at construction and repair
According to the requirement of the Swedish Road Administration pre-casting of submerged cast concrete has to be performed in two different types of moulds with a prescribed concrete with a settled grading curve of the material in the fresh mix proportion [14-16]. The two types of moulds have the following two purposes [14-16]:
- Ability of filling and covering reinforcement
- Self-levelling without compaction
For these purposes the following sizes of moulds, 2 x 1 x 1 m and 4 x 0.5 x 1 m, are used (length x width x height). Mix proportions of the concrete are to be documented and tested until 90 days’ age. The remaining requirements are as follows:

- Design values for concrete strength class C20/25 are to be used
- The concrete thickness is to be minimum 1 m
- The foundation slab is to be without cracks
- Horizontal joints are not allowed
- Agitator truck is to be used at delivery of ready mix
- The lowest concrete strength class is C28/35
- Minimum 350 kg/m³ cement is to be used
- Filler content (< 0.25 mm) is to be > 8%
- Concrete without anti-washout powder is to have slump > 120 mm
- Retarding agent is to be included in the mix proportions and the setting checked
- Non-frost resistant concrete may be used
- Anti-washout powder is to be used when statically reinforcement is included

The following requirements seem to exist as to describe the routines at submerged repair [14,17]:

- Cleaning with chisel cutting, shot pealing or blasting
- Repair extent
- Repair methods
- Material

For repair of mainly minor faults the following is described [14,17]:

- Methods how to reach the place of repair, caisson, dry or wet groove
- Methods to remove and prepare concrete
- Mix proportions of concrete repair material
- Techniques for repair
- Strengthening and pre-stressed reinforcement

### 2.3 Testing methods and frost resistance

Several methods used for NC may not be used for material meant for underwater concreting where much more viscous material is used [14,18]. The stream test was developed in Belgium. It consists of a 2 m long and 0.10-0.15 m wide 20° sloping channel with the concrete placed in the middle. The amount of washout material is not quantified only judged visually. The drop test consists of a scoop that is placed in water. By visual judgement of the muddiness of the water the tendency of washout is determined [14,19]. A pH factor test was suggested in Japan to determine the risk of washout of a concrete sample. The Plunge tests was also developed in Belgium and is used at the University of Ghent [14,20]. The cage contains holes with 3-mm diameter. The weight of the cage with concrete is taken before and after it has been sank three times underwater in a larger pipe. A mould within the apparatus is filled with about 1 kg concrete and sprayed with constant water pressure for 4 min. The loss of material is weighed. The Orimet test gives the flow ability for SCC [14,21]. The time to empty the Orimeter is measured in the test. A modified L-box was designed, which may be used with underwater concrete without anti-washout additive and for with underwater concrete with anti-washout additive and SCC [14]. Frost resistance for concrete with VMA was studied for w/b = 0.32, w/b = 0.40 and w/b = 0.45 [22]. Two types of VMA were used: a natural polymer, welan gum, G, and semisynthetic polymer, hydroxypropyl methylcellose, HPMC. The test results indicate that the air-entraining admixture, AEA, was most effectively added after VMA and the superplasticiser, which was a different mixing order to that normally is used, i.e. AEA entered in the beginning of the mixing together with the water [22]. First of all the spacing factor vs the air content was settled at w/b = 0.47, Fig. 1. The following equation was obtained (w/b = 0.47):

\[ L_{w/b=0.47} = 0.012 \cdot \Lambda^{-1.1} \]  

(1)
A denotes the air content
L denotes the spacing factor (mm)

Once the AEA was sufficiently well entrained into the concrete it seemed as if the spacing factor became sufficiently low [22]. About A = 8% coincided with L = 0.20 mm which is a normally required spacing factor in order to obtain good salt-frost resistance of concrete. Fig. 2 shows the spacing factor versus the hardened air content [22]. It became clear that the spacing factor depended both on w/b and the air content. The following equation was found based on Figs. 1-2

\[ L = 0.05 \cdot (w/b-0.26) \cdot A^2 \cdot (w/b-1) \quad (2) \]

Normally there is a clear effect of the specific surface on the salt frost scaling, Fig. 3. Fig. 3 shows that a higher specific surface was required to obtain the same salt frost scaling for concrete with VMA as for NC. For concrete with w/b = 0.45 a relationship existed between salt frost scaling and the specific surface but not for concrete with lower w/b, Fig. 4 [22]. This in turn was most probably an effect of self-desiccation, i.e. at low w/b a great part of the air voids were formed due to the chemical shrinkage of water during hydration [23,24]. Still, the salt frost scaling reported seemed to be very high, normally only a tenth of the values in Figs. 3-4 are acceptable [22].

3. Materials and methods

3.1 Material

Crushed gneiss (E-modulus 61 GPa and strength 230 MPa), pea gravel, crushed sand, natural sand, limestone filler (brand Limus 40), Fortico blended cement (CEM II/A-D-52,5, 7.5% silica fume), granulated silica fume (brand Elkem Micropoz) and Degerhamn cement (CEM I42.5BV/SR/LA) were used in the mix compositions, Fig. 5-8, Appendices 1-3. Melamine-based superplasticiser was used for NC (brand: Flyt 97M), polycarboxyl ether for SCC (brand Glenium 51) and air-entertainment agent based on fir oil and fatty acids (brand: Microair). The materials were put in steel barrels to maintain a constant moisture level. The concrete was mixed in compulsive mixers, a 40-l one in the laboratory and 1000-l one in the field [25]. The following mixing order was used:
1. Mixing dry material, air-entrainment and water ½ min.
2. Mixing with superplasticiser 2½ min.

3.2 Manufacture of specimen

One third of the specimen was NC, one third was SCC core drilled at different locations in the field [25] and one third SCC cast in the laboratory in an L-box, in the following way, Fig. 7 [25]:
1. Casting and curing in water followed by core drilling either at the near (N, close to the shaft) or at the remote end (R) of the L-box.
2. Internal frost thaw resistance in fresh, distilled water: 3 cylinders 50 mm in diameter and 150 mm in height.
3. Salt frost thaw scaling with 3% sodium chloride for NC and SCC cast in the laboratory: 3 discs 94 mm in diameter and 40 mm in height.
4. Salt frost thaw scaling with 3% sodium chloride for NC and SCC cast in the laboratory: cubes subjected to freezing at one side only.

The field test was carried out with submerged cast concrete in a full-scale beam, 0.25 x 1 x 6 m. At the field test one side of mould consisted of a prefabricated concrete element and the other side of wood or transparent glass fibre, Fig. 8 [25]. The mould was filled with water before the casting took place. The cores, 50 x 150 mm, for test of internal frost resistance, were taken by core drilling. Of each concrete 3 specimens were used from each corner of the beam, i.e. a total of 36 cores. The age of the concrete at the start of the testing was 90 days.

3.3 Methods

The adequacy of resistance of a given concrete to frost attack was determined by freezing and thawing tests described by ASTM 666-92. The tests continued until 300 cycles or until the dynamic elastic modulus was reduced to 60% of its original value [26]. The damage was assessed
after 100 and 300 of frost cycles between +20 °C and – 20 °C of freezing and thawing in distilled water with two full cycles per day. The conditions of ASTM 666-92 are more severe than those occurring in practice since the prescribed heating and cooling cycle is between + 4 °C and – 18 °C at a rate of cooling of 14 °C/h. In most part of the world, a rate of 3 °C/h is rarely exceeded [26]. The tests were started at about 90 days’ age. For tests of internal freezing and thawing resistance cylinders 50 mm in diameter and 150 mm long were placed in distilled water solution after 14 days of pre-storage in water saturated with lime. The specimen was placed in a rubber container, fully immersed in distilled water, Fig. 9. The frost thaw cycle varied between – 20 °C and 20 °C, twice a day. Cooling rate of specimen at internal freezing was around 12 °C and the heating rate varied between 10 °C/h and 20 °C. Compared with ASTM 666-92 the cooling rate was slightly lower but still much more severe than that in practice. The weight and the fundamental resonance frequency, FRF, of the specimen were observed after 100 and 300 cycles. The decrease of the elastic modulus due to internal damages was obtained by measurement of the FRF in a Grindosonic apparatus. The decrease of the elastic modulus is of interest primarily in a comparison of different concrete, preferably when only one variable is changed. Generally, a value smaller than 40 means that the concrete is probably unsatisfactory, values between 40 and 60 are regarded as doubtful while values over 60 indicate that the concrete is probably satisfactory [14]. More than 60% loss of elastic modulus, i.e. more the 40% loss of FRF, at 300 cycles is unsatisfactory for the internal frost resistance. Salt freezing and thawing resistance of NC and of SCC cast in the laboratory was studied by a method previously used at Lund University [27] which is similar to the CDF-method [28]. For test of salt frost thaw scaling cylinders 100 mm in diameter and 40 mm long were placed in 3% sodium distilled water solution after 14 days of pre-storage in water saturated with lime. The specimen was placed in a plastic container, fully immersed, Fig. 10. The frost thaw cycle varied between – 20 °C and 20 °C, twice a day. The maximum temperature was slightly lower than in tests with internal frost resistance but also lower the temperature. A minimum temperature less than 18 °C is of great importance for damages to occur. At these tests the minimum temperature well was below 20 °C. The cooling rate varied between 12 °C/h and 14 °C/h the air temperature cooling rate being shown with a dotted line. The scaling of the specimen was observed after 28, 56 and 112 cycles. Good salt freezing and thawing resistance is supposed with a one-side scaling less than 0.5 kg/m² and very good salt freezing and thawing resistance at less than 0.2 kg/m². This method consist of an all-side freezing which is supposed to be more severe the one-side testing procedure. In case of SCC cast in the field one side of a 150-mm cube was exposed to 3% sodium chloride and frozen one full cycles per day, ± 20 °C. A water-cured cube, 100-mm, was tested for strength at a rate of 1 MPa/s in a Seidner testing machine. The testing machine was calibrated. The accurate strength would be 1 MPa higher. An eccentricity in placing the cube or the cylinder may have affected the test result. The fault of eccentricity was less than 1 mm. The hourglass shape of fragments after testing the cube indicated a highly centric placing. At high strength a circular conical part of the cube remained after testing. From the field beams Ø100 x 100 mm cylinders cored were tested after grinding of the ends. An image analysis of cores drilled out from the field concrete was performed assuming a content of cement of 35% by volume.

4. Results

The grading curve of the laboratory concrete was calculated for sieves 0.063 - 11.2 mm [25]:
\[ s = 0.54 \cdot d^{0.38} \]  
(3)
d denotes sieve diameter (mm) 
s denotes material passing through

The grading curve of the field concrete was defined by on average particle size and slope [29]:
\[ s = 0.53 \cdot d^{0.36} \]  
(4)
Strength results of NC are shown in Fig. 11 [25]. Fig. 12 shows on average 28-day strength of the laboratory concrete and Fig. 13 the 28-day strength of concrete that was cast in the field [29]. Figs
14-15 show that all NC except for one concrete with w/b = 0.45 and 11% air content and one SCC with w/b = 0.48, did not fulfil the ASTM 666 requirements as concerns internal loss of FRF, i.e. elastic modulus to be larger than 60% of the original value after 300 cycles. Eight of 12 concrete were totally destroyed even before 100 frost cycles. Concrete with anti-wash out powder was not durable to internal freezing and thawing at w/b = 0.45 even through 8% air content was studied. Concrete at w/b = 0.46 with anti-wash out powder was durable to internal freezing and thawing when 11% air content was studied. However, at high air content the strength became too low. SCC with w/b = 0.48 and 6% air content exhibited a high grade of internal freezing and thawing resistance. Only 4.5% loss of FRF and 0.9% loss of weight after 300 frost cycles was observed. These results confirm the previous studies that SCC generally is more resistant to internal freezing and thawing attack than NC is [30]. Figs 16-17 show the performance of internal frost resistance of concrete that was cast in the laboratory. Concrete with w/b = 0.35 and w/b = 0.40 showed good internal frost resistance both related to FRF (less than 15% losses after 300 cycles) and scaling (no loss of weight). Small losses of FRF were observed of concrete that was cast at the remote end of the L-box. At w/b = 0.45 large weight loss was obtained at the remote end of casting in the L-box. Figs 18-19 show internal frost resistance of SCC that were cast in the field, i.e. large loss of FRF in SCC with w/b = 0.35 [29]. Fig. 20 show large salt frost scaling for all NC with anti-wash out powder, not durable to salt freezing and thawing scaling even through as much as 8% air content was studied at w/b = 0.45. SCC, with w/b varying between 0.35 and 0.40 exhibited an excellent salt freezing and thawing resistance at the near end of the L-box at casting. At the remote end of the L-box air probably was washed out which reduced the freezing and thawing resistance. Eight percent of air content was required in order to fulfil freezing and thawing resistance at the remote end of the L-box at casting submerged SCC except for w/b =0.45. For w/b = 0.45 not even 8% air content was enough to fulfil a salt freezing and thawing scaling of less than 0.5 kg/m² as indicated by the dotted line in Fig. 20. One indirect way of determine the effect of difference in air content may be to observe the density. The diameter and the length of all specimens were established before the freezing tests were carried out. Fig 21 show large differences between the density at crest and foot of of SCC with w/b = 0.40 and w/b = 0.45, cast in the field, due to segregation of aggregate [25].

5. Discussion

5.1 SCC cast in the laboratory

The concrete were designed to contain 1%, 4% or 8% air content. Fig. 22 shows the change of FRF at the near and the remote end of L-box (4 = 4% air content, 35 = w/b (%)). Especially for concrete 45S8 an increased loss of FRF was observed. The loss of FRF was 9 times as high at the remote end of the L-box as close to the pouring place. As concerns concrete 45S8 the density and the strength indicate that the air content performed at the casting of concrete 45S8 was much lower than 8%, probably about 3% air content. Still the difference in density between the near and the remote end of casting was small. If air had left the concrete then the density would increase with 10 kg/m³ per percent of decrease of air. If segregation took place during the casting in the L-box, i.e. more fines were transported to the end of the L-box then the density would decrease. Probably both phenomena took place during casting in the L-box: some air content left the concrete, about 2%, which increased the density with about 20 kg/m³. In parallel some segregation took place in the concrete with w/b = 0.35 and with w/b = 0.45, influencing a change of density of about 30 kg/m³. However, for concrete with w/b = 0.40 and 8% air content the separation was less, maybe affecting density with 10 kg/m³ only. The results for concrete 45S8 thus resulted in too low air content at the end of the L-box and thus too large loss of internal frost resistance, about 80% loss of FRF. Concrete 45S8 was almost destroyed at the remote end of the casting place. Fig. 23 shows the change of FRF after 300 cycles in fresh water at the remote end of casting in the L-box. Still, for concrete with w/b = 0.45, the real air content probably was only about 1%, i.e. too low for the
concrete 45S8 to resist internal frost. At w/b = 0.35 and at w/b = 0.40 also some self-desiccation took place which caused internal air voids to form and thus good internal frost resistance of the concrete [25]. The change of FRF after 300 cycles in fresh water at the near end of casting in the L-box, before segregation of aggregate, which did not take place close to the pouring place in the L-box, and before loss of about 3% air, the air content of concrete 45S8 was sufficiently large for the concrete to withstand internal frost for 300 cycles in fresh water, even at w/b = 0.45. About 3% air content was sufficient for the concrete 45S8 to resist internal frost for 300 cycles, at near end of casting in the L-box.

5.2 Concrete that was cast in the field
The fresh concrete that was cast in the field was designed to contain between 3.5% and 6.6% air content. Fig. 21 shows the difference in density at different positions of casting. As expected the density diminished at the crest of casting, quit substantially and in the contrary increased at the bottom of the mould due to aggregate separation, probably. The difference in density may also be related to movement of air in the fresh mix, upwards, which then also would increase the density at the bottom of the mould. Generally, the increase of density at the bottom of the moulds was 40 kg/m³, which coincide well with 4% of air content leaving the mix at the bottom of the mould. At the foot of casting also an increase of strength systematically took place, which either was a result of the increasing content of aggregates or the result of a decrease of the air content. The main differences of density in the concrete were observed vertically, i.e. either some aggregate moving downwards or air leaving the bottom of the mixed fresh concrete. Fig. 24 shows that the largest decrease of FRF took place at the crest of the casting, which shows that the difference of air content was not the reason for density difference but the segregation of aggregates. If the difference of the density would be related to air leaving the mix at the bottom the air content at the top of the casting would be higher than foreseen and then the decrease of FRF lower than observed. The decrease of FRF was also slightly related to w/b of the concrete, larger loss of FRF at low w/b = 0.35 than at w/b = 0.45. Still the decrease of FRF was small, 20 % maximum, i.e. less than the acceptable loss of FRF, which is 40% [26]. Fig. 24 shows the decrease of FRF at the remote end of the casting. At the remote end of casting the loss of FRF became much larger than at the near end. At the near end of casting in the field the losses also were larger than these observed in the L-box at the laboratory tests with concrete, since no vertical segregation took place in the L-box but certainly in the field. This tends to indicate that air also left the mix proportions between casting at the near end and during the transport, horizontally, in the mould also seen in Fig. 21, which shows an increase of density at the far end of casting compared with the near end. Two phenomena thus acted in parallel, air leaving the concrete and aggregate segregation. However, aggregate and air separation was related to w/b = 0.45 at which concrete quality it was pronounced – only minor at w/b = 0.35 and w/b = 0.40. Fig. 25 shows the change of FRF versus the change of density at the near end of casting. An increase in density resulted in larger decrease of FRF. For the other position of casting no correlation was found between change of density and decrease of FRF. Large decrease of FRF occurred at no change of density at all, which indicted that the density decreased just as much due to aggregate separation as the density increased due to air content losses. Image analysis of cores drilled out from the field concrete assuming a content of cement of 35% by volume shows quite different air content between fresh and hardened air content in the concrete, Fig. 26. The air content was about 50% larger in the hardened state than in the fresh one. It also was about 75% larger in concrete with w/b = 0.45 than in concrete with w/b = 0.35. The failure of internal frost resistance at w/b = 0.35 probably was explained by too low a air content, only 3.5% at w/b = 0.35. Salt-frost scaling after 112 cycles of the field concrete was correlated the hardened air content in the following way, Fig. 27:

\[ m_{\text{saltfrost, 112 c.}} = 380 \cdot A^{-3.93} \]  

\[ m_{\text{saltfrost, 112 c.}} \] denotes salt-frost scaling at 112 cycles (kg/m²)  
\[ A \] denotes hardened air content (%)
The spacing factor of the field SCC showed good correlation to a combination of w/c and the air content, Fig. 28. Fig. 28 shows the spacing factor calculated according to equation (2). No correlation existed between the salt-frost scaling and the spacing factor of the field SCC, Fig. 29.

6. Conclusions

After studies of frost resistance of a large number of NC, and SCC, cast both in the laboratory and in the field the following conclusions were drawn:

1. At w/b = 0.35 internal frost resistance of the field concrete failed due to too a low air content.
2. Salt-frost scaling of field concrete with w/b = 0.35 fulfilled the requirements.
3. At w/b = 0.40 all concrete with about 5% air content fulfilled all conditions of frost resistance.
4. Increase of air entrainment was required in order to obtain salt frost resistance at w/b = 0.45.
5. Submerged cast concrete with w/b > 0.45 was not frost resistant even with large air content.
6. Lower frost resistance was observed at the remote end of casting than near end of the casting.
7. Lower frost resistance was due to segregation that was confirmed by measurement of density.

Acknowledgement

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References

17. Design and Performance of Submerged Concrete, Appendix 3, Norwegian Concrete Association (1994).
Persson, SCC for submerged repair

\[ y = 0.012x^{-1.1} \]

\[ R^2 = 0.93 \]

Fig. 1 - Spacing factor vs air content.

Fig. 2 - Spacing factor vs air content.

Fig. 3 - Salt frost scaling versus specific surface for concrete with VMA and for NC.

Fig. 4 - Salt frost scaling versus specific surface for concrete with w/b = 0.32 - 0.45.

Fig. 5 – Grading curves of the materials.

Fig. 6 – Grading curves of the field materials.
Fig. 7 – Bottom of L-box filled with water before a sliding gate was opened at the end of the box to cast concrete from the vertical shaft submerged into the box and to cure it.

Fig. 8 – Field test with one side of mould of a prefabricated concrete element and the other of wood or transparent glass fibre. Photo: Iad Saleh.

Fig. 9 - Specimen in rubber container, immersed in distilled water (internal frost).

Fig. 10 - Specimen for tests of salt freezing and thawing scaling in 3% sodium water.
Fig. 11 – NC strength at 28 days’ age. A = air content (%), S = SCC.

Fig. 12 - Strength of SCC cast in the laboratory. A = air content (%).

Fig. 13 – Strength of SCC cast in the field. C = crest; F = foot; N = near pump; R = remote.

Fig. 21 – Density depending on the position of casting versus w/b (Fig. 13). 35 = w/b (%).
Fig. 14 - Internal freezing and thawing resistance, FRF, after 100 and 300 cycles of NC. S = SCC; U = submerged concrete; 2 = air content (%); 45 = w/b (%).

Fig. 15 - Internal freezing and thawing resistance, loss of weight, after 100 and 300 cycles of NC. S = SCC; U = submerged concrete; 2 = air content (%); 45 = w/b (%).

Fig. 16 - Internal frost resistance, FRF, after 100 and 300 cycles of concrete cast in the laboratory. 35 = w/b (%); N = near end of casting; R = remote; S = 7.5% silica fume; 4 = air content (%).

Fig. 17 - Internal frost resistance, loss of weight, after 100 and 300 cycles of cast in the laboratory. 35 = w/b (%); N = near end of casting; R = remote; S = 7.5% silica fume; 4 = air content (%).
Fig. 18 - Internal frost resistance, FRF, after 100 and 300 cycles of SCC cast in the field. 35 = w/b (%); S = 7.5% silica fume; 4 = air content (%); C = crest; F = foot; N = near the; R = remote.

Fig. 19 - Internal frost resistance, FRF, after 100 and 300 cycles of concrete cast at Farsta. 35 = w/b (%); S = 7.5% silica fume; 4 = air content (%); C = crest; F = foot; N = near the; R = remote.

Fig. 20 – Salt freezing and thawing resistance. N = near the casting place; R = remote; Reference cast above water; S = 7.5% silica fume; U = submerged concrete; 2 = air content (%); 45 = w/b (%).

Fig. 22 – FRF change at the near and remote end of L-box. 4 = 4% air, 35 = w/b (%).

Fig. 23 – FRF change after 300 cycles in fresh water at remote casting end of the L-box.
Fig. 24 - Decrease of FRF at the remote end of the casting. 35 = w/b (%).

Fig. 25 - Decrease of FRF at the near end of the casting.

Fig. 26 – Harden air content (image analysis). C = crest; F = foot; N = near; R = remote.

Fig. 27 – Salt-frost scaling after 112 cycles versus hardened air content.

Fig. 28 – Spacing factor versus air content. 35 = w/b (%). [22] = reference [22].

Fig. 29 – Salt-frost scaling versus spacing factor (no correlation). 35 = w/b (%).
### Appendix 1 – Mix composition and properties of NC and SCC (kg/m³).

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<td>1.16</td>
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<td>1.59</td>
<td>1.51</td>
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<td>11</td>
<td>4</td>
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<td>3</td>
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<td>1</td>
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<td>1.8</td>
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<td>255</td>
<td>140</td>
<td>260</td>
<td>225</td>
<td>240</td>
<td>50</td>
<td>250</td>
<td>230</td>
<td>275</td>
<td>235</td>
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<tr>
<td>Slump flow (mm)</td>
<td>460</td>
<td>500</td>
<td>480</td>
<td>570</td>
<td>370</td>
<td>450</td>
<td>350</td>
<td>510</td>
<td>500</td>
<td>530</td>
<td>460</td>
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<td>L-box</td>
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<td>0.43</td>
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<td>0.28</td>
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<td>0.51</td>
<td>0.51</td>
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<td>0.46</td>
<td>0.48</td>
<td>0.33</td>
<td>0.48</td>
<td>0.49</td>
<td>0.49</td>
<td>0.50</td>
<td>0.51</td>
<td>0.51</td>
<td>0.55</td>
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<td>2084</td>
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<td>2365</td>
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<td>2361</td>
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<td>2354</td>
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<td>Aggregate/Cement</td>
<td>4.11</td>
<td>4.11</td>
<td>4.31</td>
<td>4.42</td>
<td>4.31</td>
<td>4.31</td>
<td>4.45</td>
<td>4.21</td>
<td>4.64</td>
<td>4.32</td>
<td>5.09</td>
<td>4.32</td>
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<td>Aggregate/Density</td>
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<td>0.74</td>
<td>0.74</td>
<td>0.69</td>
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<td>0.74</td>
<td>0.74</td>
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<td>0.74</td>
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<td>0.77</td>
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<td>Aggregate/Powder</td>
<td>4.11</td>
<td>4.11</td>
<td>4.31</td>
<td>3.01</td>
<td>4.31</td>
<td>4.31</td>
<td>4.45</td>
<td>4.21</td>
<td>4.64</td>
<td>4.32</td>
<td>5.09</td>
<td>4.32</td>
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<tr>
<td>Strength, 28 days (MPa)</td>
<td>50.5</td>
<td>27.5</td>
<td>63.0</td>
<td>76.0</td>
<td>61.4</td>
<td>59.3</td>
<td>60.0</td>
<td>68.0</td>
<td>65.0</td>
<td>59.0</td>
<td>33.6</td>
<td>26.0</td>
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Appendix 2 – Mix composition and properties of SCC cast in the laboratory (kg/m³).

<table>
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<tr>
<th>Concrete</th>
<th>35S1</th>
<th>35S4</th>
<th>35S8</th>
<th>40S4</th>
<th>40S8</th>
<th>45S8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lenzhard 4-8 mm</td>
<td>480</td>
<td>464</td>
<td>452</td>
<td>457</td>
<td>444</td>
<td>446</td>
</tr>
<tr>
<td>Lenzhard 0-4 mm</td>
<td>633</td>
<td>612</td>
<td>596</td>
<td>602</td>
<td>585</td>
<td>588</td>
</tr>
<tr>
<td>Crushed stone 2-4 mm</td>
<td>208</td>
<td>201</td>
<td>196</td>
<td>198</td>
<td>192</td>
<td>193</td>
</tr>
<tr>
<td>Quartzite sand 0.1-1 mm</td>
<td>306</td>
<td>295</td>
<td>288</td>
<td>291</td>
<td>283</td>
<td>284</td>
</tr>
<tr>
<td>Limestone powder Köping 500</td>
<td>141</td>
<td>136</td>
<td>133</td>
<td>177</td>
<td>172</td>
<td>214</td>
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<tr>
<td>Blended cement Fortico 5R</td>
<td>470</td>
<td>454</td>
<td>442</td>
<td>405</td>
<td>393</td>
<td>354</td>
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<tr>
<td>Air-entrainment (fir oil)</td>
<td>0.0000</td>
<td>0.045</td>
<td>0.124</td>
<td>0.150</td>
<td>0.252</td>
<td>0.244</td>
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<tr>
<td>Water</td>
<td>169</td>
<td>164</td>
<td>159</td>
<td>162</td>
<td>157</td>
<td>159</td>
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<tr>
<td>Glenium 51 (wet)</td>
<td>9.17</td>
<td>8.86</td>
<td>8.63</td>
<td>8.72</td>
<td>8.48</td>
<td>8.52</td>
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<td>Glenium 51 (%/powder)</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.2</td>
<td>2.2</td>
<td>2.4</td>
</tr>
<tr>
<td>Density</td>
<td>2419</td>
<td>2335</td>
<td>2275</td>
<td>2301</td>
<td>2236</td>
<td>2248</td>
</tr>
<tr>
<td>Air content (%)</td>
<td>1.1</td>
<td>3.9</td>
<td>7.0</td>
<td>5.0</td>
<td>7.9</td>
<td>7.4</td>
</tr>
<tr>
<td>Slump flow Ø (mm)</td>
<td>750</td>
<td>735</td>
<td>735</td>
<td>740</td>
<td>750</td>
<td>750</td>
</tr>
<tr>
<td>L-box</td>
<td>0.72</td>
<td>0.53</td>
<td>0.88</td>
<td>0.93</td>
<td>0.94</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Strength (MPa)

| 2 days, average | 58.8 | 68.3 | 61.5 | 45.5 | 45.3 | 37.3 |
| 28 days, average | 118.0 | 99.5 | 99.3 | 73.8 | 84.0 | 83.8 |
| 90 days, average | 115.5 | 115.3 | 93.0 | 90.3 | 90.3 | 90.5 |

35 = w/b (%); 1 = air content (%).

Appendix 3 – Mix composition and properties of SCC cast in the field (kg/m³).

<table>
<thead>
<tr>
<th>Concrete</th>
<th>35</th>
<th>40</th>
<th>45</th>
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</thead>
<tbody>
<tr>
<td>Cement, c</td>
<td>430</td>
<td>400</td>
<td>375</td>
</tr>
<tr>
<td>Limestone filler</td>
<td>160</td>
<td>170</td>
<td>200</td>
</tr>
<tr>
<td>Silica fume</td>
<td>26</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Water, w</td>
<td>160</td>
<td>170</td>
<td>181</td>
</tr>
<tr>
<td>Sand 0-2 mm</td>
<td>247</td>
<td>256</td>
<td>244</td>
</tr>
<tr>
<td>Gravel 0-8 mm</td>
<td>791</td>
<td>784</td>
<td>777</td>
</tr>
<tr>
<td>Aggregate 8-16 mm</td>
<td>610</td>
<td>560</td>
<td>503</td>
</tr>
<tr>
<td>Air entrainment (% of c)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Superplasticizer (% of c)</td>
<td>1.3</td>
<td>1.1</td>
<td>0.8</td>
</tr>
<tr>
<td>w/b</td>
<td>0.35</td>
<td>0.40</td>
<td>0.45</td>
</tr>
<tr>
<td>Slump flow (mm)</td>
<td>640</td>
<td>640</td>
<td>630</td>
</tr>
<tr>
<td>Density</td>
<td>2424</td>
<td>2366</td>
<td>2305</td>
</tr>
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<td>Air content (%)</td>
<td>3.5</td>
<td>4.8</td>
<td>5.6</td>
</tr>
<tr>
<td>Strength (MPa)</td>
<td>97.5</td>
<td>86</td>
<td>60</td>
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