SALT FROST RESISTANCE OF SELF-COMPACTING CONCRETE

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Abstract
In this article salt-frost resistance of Self-Compacting Concrete in several projects are outlined. For this purpose first of all a summing up of international research is presented. Then results of experiments including both laboratory and field tests are analysed. The parameters water-cement ratio, additives, admixtures, cement types, fibres and in-situ effects are studied. The results indicate that salt frost scaling of Self-Compacting Concrete does not differ much from the analogous property of normal concrete provided that the tested sample are laboratory produced. However, air entrainment in Self-Compacting Concrete as well as viscosity agent and polypropylene fibres may affect the salt frost scaling in another way than in normal concrete. The superplasticiser polycarboxylic ether itself produces air entrainment which makes the dosage of air entrainment agent difficult to establish in an accurate way. Both viscosity agent and polypropylene fibres in Self-Compacting Concrete seems to reduce the salt frost scaling durability substantially. For Self-Compacting Concrete produced in practise segregation of aggregate are essential factors to take into account since these are much more dictating for salt frost scaling of Self-Compacting Concrete than for normal. Segregation of aggregate in Self-Compacting Concrete affects the water-cement ratio which leads to a substantial decrease of salt frost scaling durability of Self-Compacting Concrete.

1. INTRODUCTION
Extensive long-term salt frost damage to high-way constructions in concrete has been observed, mainly due the use of de-icing salt. The high-way constructions were cast perhaps 50 years ago when the knowledge of the influence of air-entrainment and low water-cement ratio, w/c, on the salt frost resistance was hardly known. For highway bridges, freezing may likewise take place under influence of salt water on the bridge deck, causing risk of surface deterioration due to absorption and saturation of water in the surface pores where no escape way is found for the freezing water or frozen ice. When the distance between the empty air voids exceeds the spacing factor then damage may occur. An initial parameter study showed less salt frost scaling with larger air and silica fume content and with larger specific surface of the air voids. On contrary larger w/c and more fly ash and slag in the SCC lowered the resistance to salt frost attack. In parallel larger w/c gave larger capillary sorption of the SCC and thus larger salt frost scaling. The highest accepted spacing factor required for concrete durable to salt frost is normally judged to be 0.20 mm combined with a minimum air void content varying between 4% and 6% dependent on w/c [1,2].
2. MATERIAL AND METHODS

2.1 Symbols
AEA  air-entrainment agent  
B  increased amount of filler  
C  close to casting place  
D  distant from casting place  
H  high point of casting  
K  40 µm limestone filler  
L  spacing factor (mm)  
N  new mixing order (filler last)  
NC  normal compacted concrete with ordinary mixing order (filler first)  
PPF  polypropylene fibres  
R  NC  
S  15 µm limestone filler  
Sc  salt frost scaling (kg/m²)  
SF  silica fume (%)  
T  5.5 m hydrostatic pouring pressure  
U  underneath the casting  
VMA  viscosity modifying agent  
II  second casting  
28  28 days’ age at start of testing

2.2 Material
Quartzite sandstone (E-modulus 61 GPa and strength 330 MPa), crushed gneiss (E-modulus 61 GPa and strength 230 MPa), natural sand, limestone filler (40 µm), granulated silica fume and CEM I 42.5BV/SR/LA were used in the mix compositions, Tables 1-3 [3-5]. Melamine-based superplasticiser was used for NC, polycarboxylic ether for SCC (both in wet weight of which 35% dry material) and AEA based on fir oil and fatty acids (in wet weight of which 10% dry material). VMA, natural or synthetic, was used. The concrete was mixed in a 40-l or 1000-l compulsive mixer in the laboratory. The following mixing order was used:
1. Mixing dry material, air-entrainment and water ½ min.  
2. Mixing with superplasticiser 2½ min.  
Concrete according to Table 1 was cast in large specimens with diameter 0.3 m and length 0.3 m from which cylinders 100 mm in diameter were core drilled at 28 and 90 days’ age [3]. The cylinders were then cut at 40-mm length, three of each combination. Concrete according to Table 2 was cast in an L-box form from which cylinders of Ø 100 x 40 mm³ were core drilled and cut, 3 of each combination at 28 days’ age [4]. Concrete with PPF was made as cylinders Ø 100 x 200 mm³ from which discs 40 mm long were cut, Table 3 [5]. The tests started 1 month’ age for concrete given in Table 2 and at 10 months’ age concrete in Table 3.

2.3 Methods
Salt frost resistance was studied by a method previously used by Lindmark [1] which is similar to the CDF-method [6]. For tests of salt frost scaling cylinders 100 mm in diameter and 40 mm long were placed in 3% sodium chloride in distilled water solution after 14 days of pre-storage in water saturated with lime. The specimen was placed in a plastic container,
fully immersed. The salt frost thaw cycle varied between –20 °C and 20 °C, twice a day. At these tests the minimum temperature well was below 20 °C. The cooling rate varied between 12 °C/h and 14 °C/h. The scaling of the specimen was observed after 28, 56 and 112 cycles.

Table 1: Mix composition and properties of NC and SCC [3].

<table>
<thead>
<tr>
<th>Material/mix composition</th>
<th>KN</th>
<th>KOB</th>
<th>KN8</th>
<th>KO</th>
<th>KOT</th>
<th>SO</th>
<th>RO</th>
<th>ROII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed 8-16 mm</td>
<td>363</td>
<td>371</td>
<td>355</td>
<td>367</td>
<td>363</td>
<td>402</td>
<td>862</td>
<td>876</td>
</tr>
<tr>
<td>Sand 0-8 mm</td>
<td>853</td>
<td>872</td>
<td>836</td>
<td>864</td>
<td>855</td>
<td>786</td>
<td>715</td>
<td>727</td>
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<tr>
<td>Sand 0-2 mm</td>
<td>316</td>
<td>135</td>
<td>309</td>
<td>320</td>
<td>316</td>
<td>422</td>
<td>146</td>
<td>149</td>
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<tr>
<td>Limestone filler</td>
<td>183</td>
<td>375</td>
<td>180</td>
<td>186</td>
<td>184</td>
<td>94</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>CEM I</td>
<td>418</td>
<td>427</td>
<td>409</td>
<td>423</td>
<td>419</td>
<td>416</td>
<td>431</td>
<td>438</td>
</tr>
<tr>
<td>Air-entr. (g, 10%)</td>
<td>585</td>
<td>213</td>
<td>1203</td>
<td>106</td>
<td>117</td>
<td>125</td>
<td>474</td>
<td>482</td>
</tr>
<tr>
<td>Superplast. (35%)</td>
<td>2.97</td>
<td>4.13</td>
<td>3.2</td>
<td>3.39</td>
<td>3.69</td>
<td>2.99</td>
<td>7.32</td>
<td>5.92</td>
</tr>
<tr>
<td>Water</td>
<td>163</td>
<td>167</td>
<td>160</td>
<td>165</td>
<td>163</td>
<td>162</td>
<td>168</td>
<td>171</td>
</tr>
<tr>
<td>w/c</td>
<td>0.39</td>
<td>0.39</td>
<td>0.39</td>
<td>0.39</td>
<td>0.39</td>
<td>0.39</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>w/p</td>
<td>0.27</td>
<td>0.21</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
<td>0.32</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>Air cont. (%)</td>
<td>5.6</td>
<td>4.9</td>
<td>8</td>
<td>5.5</td>
<td>6.3</td>
<td>5.6</td>
<td>5.8</td>
<td>6.1</td>
</tr>
<tr>
<td>28-day strength (MPa)</td>
<td>63</td>
<td>84</td>
<td>50</td>
<td>75</td>
<td>75</td>
<td>61</td>
<td>68</td>
<td>63</td>
</tr>
<tr>
<td>Slump (mm)</td>
<td>720</td>
<td>780</td>
<td>735</td>
<td>620</td>
<td>640</td>
<td>710</td>
<td>110</td>
<td>150</td>
</tr>
<tr>
<td>Flow time (s)</td>
<td>5</td>
<td>7</td>
<td>8</td>
<td>10</td>
<td>8</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Density</td>
<td>2297</td>
<td>2348</td>
<td>2250</td>
<td>2323</td>
<td>2300</td>
<td>2285</td>
<td>2325</td>
<td>2368</td>
</tr>
</tbody>
</table>

B = increase of filler; K = 40 µm limestone filler; N = new way of mixing (filler last); O = ordinary; R = NC; S = 15 µm limestone filler; T = 5.5 m hydrostatic pressure, II = second.

Table 2: Mix composition and properties of NC and SCC with PPF (kg/m³) [4,5].

<table>
<thead>
<tr>
<th>Concrete</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>40N0</th>
<th>4000</th>
<th>40K0</th>
<th>40K2</th>
<th>42K2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartzite 11-16 mm</td>
<td>305</td>
<td>280</td>
<td>252</td>
<td>471</td>
<td>496</td>
<td>474</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>Quartzite 8-11 mm</td>
<td>305</td>
<td>280</td>
<td>252</td>
<td>139</td>
<td>146</td>
<td>189</td>
<td>208</td>
<td>208</td>
</tr>
<tr>
<td>Gravel 0-8 mm</td>
<td>791</td>
<td>784</td>
<td>777</td>
<td>1000</td>
<td>1053</td>
<td>912</td>
<td>990</td>
<td>990</td>
</tr>
<tr>
<td>Sand 0-2 mm</td>
<td>247</td>
<td>256</td>
<td>244</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Limestone filler 40 µm</td>
<td>160</td>
<td>170</td>
<td>200</td>
<td>-</td>
<td>-</td>
<td>92</td>
<td>97</td>
<td>97</td>
</tr>
<tr>
<td>CEM I 42.5 BV/SR/LA</td>
<td>430</td>
<td>400</td>
<td>375</td>
<td>441</td>
<td>464</td>
<td>430</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>AEA</td>
<td>0.194</td>
<td>0.215</td>
<td>0.200</td>
<td>0.132</td>
<td>0.093</td>
<td>0.089</td>
<td>0.125</td>
<td>0.225</td>
</tr>
<tr>
<td>Water</td>
<td>160</td>
<td>170</td>
<td>181</td>
<td>176</td>
<td>186</td>
<td>172</td>
<td>180</td>
<td>193</td>
</tr>
<tr>
<td>VMA</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Superplasticiser</td>
<td>5.6</td>
<td>4.7</td>
<td>4.4</td>
<td>2.2</td>
<td>4.6</td>
<td>5.6</td>
<td>32.4</td>
<td>33.7</td>
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<tr>
<td>Water-cement ratio</td>
<td>0.35</td>
<td>0.40</td>
<td>0.45</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
<td>0.43</td>
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<tr>
<td>Polypropylene fibres</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.4</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>2424</td>
<td>2366</td>
<td>2305</td>
<td>2227</td>
<td>2347</td>
<td>2278</td>
<td>2380</td>
<td>2394</td>
</tr>
<tr>
<td>Slump (flow) (mm)</td>
<td>640</td>
<td>640</td>
<td>630</td>
<td>180</td>
<td>620</td>
<td>640</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Air content (fresh,%)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>7.8</td>
<td>3.3</td>
<td>7.3</td>
<td>2.8</td>
<td>3.3</td>
</tr>
<tr>
<td>Air content (harden,%)</td>
<td>3.5</td>
<td>4.8</td>
<td>5.6</td>
<td>10</td>
<td>2.6</td>
<td>3.3</td>
<td>1.9</td>
<td>3.8</td>
</tr>
<tr>
<td>Spacing factor (mm)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.09</td>
<td>0.35</td>
<td>0.44</td>
<td>0.95</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Symbols: K = 40 µm limestone filler, N = NC, …0 = no PPF, 2 = 1.4 kg/m³ 18 µm PPF.
3. RESULTS AND DISCUSSION

Concrete performs excellent with less than 0.20 kg/m² salt frost scaling after 56 cycles, and good with less than 0.50 kg/m² [3]. Figure 1 shows results of salt frost scaling at 28, 56 and 112 salt frost cycles of concrete shown in Table 1 [3]. Only comparison between the different concrete may be done. SCC obtained the same salt frost scaling as NC did. The following conclusions for the tests with concrete in Table 1 may be drawn at 112 cycles [3]:

1. More filler did not increase the salt frost scaling.
2. At 28 days’ start age salt frost scaling was larger in SCC than in NC.
3. SCC with 5.5 m pouring pressure instead of 0.23 m did not obtain more salt frost scaling.
4. SCC with coarser limestone filler (40 µm) obtained more salt frost scaling than SCC with finer limestone filler did (15 µm).

Figure 2 shows salt frost scaling of concrete in Table 2 with location of specimen indicated [4]. At the distant end of casting the scaling was larger the close to the casting place. The salt frost scaling was also larger for concrete with w/c = 0.45 than for concrete with w/c = 0.35.

At w/c = 0.35 SCC without air entrainment and PPF performed excellent close to the casting place but was totally deteriorated at the distant end of casting due to segregation, Figure 3 [4]. At w/c = 0.40 4% air content was required at the distant end of casting to obtain good salt frost resistance and excellent salt frost resistance close to the casting place. For w/c = 0.45 the air requirement was 8% close to the casting place for obtaining excellent salt frost resistance close the casting place but not enough far from casting. Figure 4 shows much better salt frost resistance of NC than that of SCC [5]. Especially for concrete with PPF a sudden break-down of the surface took place. Figure 5 shows the salt frost scaling versus spacing factor. Low spacing factor also gave excellent salt frost scaling. To obtained good salt frost scaling 0.20

![Figure 1: Salt frost scaling, Table 1 [3].](image1)

![Figure 2: Salt frost scaling, Table 2 [4].](image2)
mm spacing factor seems to be a maximum, Figure 5. The following formula was suggested to estimate L (mm) of SCC from the air content (-) of concrete [7]:

\[ L = 0.05 \times (w/c - 0.26) \times A^2 \times (w/c - 1) \quad \{R^2 = 0.73\} \quad (1) \]

![Figure 3: Salt frost scaling after 56 cycles, close and distant to casting place, Table [4].](image)

![Figure 4: Salt frost scaling of SCC, with and without PPF, Table 2 [5].](image)

![Figure 5: Salt frost scaling versus spacing factor, Table 2 [5].](image)

4. CONCLUSIONS

For SCC with and without limestone filler the following conclusions were drawn [14]:
1. Salt frost scaling of SCC does not differ much from the analogous property of normal concrete provided that the tested sample are laboratory produced.
2. More limestone filler did not increase the salt frost scaling.
3. At 28 days’ start age salt frost scaling was larger in SCC than in NC.
4. At 90-day age of start of testing the salt frost scaling was less than at 28-day age of testing.
5. SCC with 5.5 m pouring pressure instead of 0.23 m did not obtain more salt frost scaling.
6. SCC with coarser limestone filler (40 µm) obtained more salt frost scaling than SCC with finer limestone filler did (15 µm).
7. For SCC much lower salt frost resistance was obtained at the distant end of casting than close to the casting place due to segregation.

For SCC with and without polypropylene fibres, PPF, the following was concluded:
1. Good salt frost durability was obtained for all concrete – excellent salt frost scaling was obtained for normal concrete.
2. At about 3% air SCC with viscosity agent, VMA, exhibits about twice as large salt frost scaling as SCC with limestone filler and PPF.
3. For SCC with 3% air content the salt frost scaling was twice as large for SCC with w/c = 0.42 as for SCC with w/c = 0.40.
4. For 7.5% fresh air content SCC with limestone filler obtained about 4 times the salt frost scaling of normal concrete.
5. At low air content an inner break down occurred in SCC with PPF.
6. At high strength SCC with PPF was damaged by salt frost attack if the air content was too low.
7. The salt frost scaling increased when the spacing factor of the harden air content increased

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REFERENCES