Improving resistance of high strength concrete (HSC) bridge beams to frost and defrosting salt attack by application of hydrophobic agent

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Abstract. HSC (High Strength Concrete) is increasingly used for bearing bridge structures nowadays. Bridge structures in the Czech Republic are exposed to severe conditions in winter time and durability of the concrete is therefore a crucial requirement. The high strength and low water absorption of HSC suggests that the material will have high durability. However, the situation may not be so straightforward. We carried out a study of the very poor durability of HSC concrete C70/85 used to produce prestressed beams 37.1 m in length to build a 6-span highway bridge. After the beams were cast, a production control test indicated some problems with the durability of the concrete. There was a danger that 42 of the beams would not be suitable for use. All participants in the bridge project finally decided, after extensive discussions, to attempt to improve the durability of the concrete by applying a hydrophobic agent. Paper will present the results of comparative tests of four hydrophobic agents in order to choose one for real application and describes this application on construction site.

1. Introduction

The problem of concrete durability is very important for transport structures in the Czech Republic. Our experience has shown that the application of HSC concrete leads to new problems in this area. The high strength and low water absorption of HSC suggests that the material will have high durability. However, the situation may not be so straightforward. In 2010-2011, we carried out a study of the very poor durability of HSC concrete C70/85 used to produce prestressed beams 37.1 m in length to build a 6-span highway bridge (see Figure 4). There was a danger that 42 of the beams would not be suitable for use. After the beams were cast, a control test indicated some problems with the durability of the concrete. This problem is not easy to solve. All participants in the bridge project finally decided, after extensive discussions, to attempt to improve the durability of the concrete by applying a hydrophobic agent.

The action of hydrophobic agents is a too broad issue to be discussed in detail in a short paper. More about this topic can be found in [1], [2], [3], [8]. The principle of hydrophobic treatment involves increasing the capillary tension of the materials and increasing the wetting angle of the water by forming a thin layer (film) of a hydrophobic agent on the inner surface of the pores of the construction materials. This layer must be extremely thin, invisible to the eye, in order to avoid reducing the diameter of the pores, which would clog them and block the vapour permeability. Surfaces treated with a hydrophobic agent do not allow water to create a continuous surface and moisten the surface. The water runs down in a bullet-like shape.
2. Experimental verification of the four hydrophobic agents

The functional behaviour of hydrophobic agents applied to concrete is specified in EN 1504-2 [4]. This standard is followed by testing standards defining a series of tests. The most important tests are:

- Test of drying rate EN 13579 [5]
- Test of water absorption through an impregnated surface EN 13580 [6]
- Test of the resistance of an impregnated surface to alkali effects EN 13580
- Determination of the depth of penetration of hydrophobic agent EN 1504-2 [4]

Concrete cubes (100 mm edge) prepared from concrete with water cement ratio w/c = 0.45 were produced for a drying test, a test of water absorption, and a test of resistance to alkalis. Cubes for depth of penetration test were prepared from concrete with water cement ratio w/c = 0.7. The test specimens were impregnated according to the instructions of the producer of the hydrophobic treatment agent. The depth of the dry (light) area (see Figure 1) was considered as the effective depth of the hydrophobic agent. Results of individual tests and normative standards are stated in table 1.

| Table 1. Results of executed tests |
|-----------------------------------|
| Parameter                        | Test label of hydrophobic treatment agent |
|                                  | A oligomeric siloxanes | B silanes | C oligomeric siloxanes | D silanes |
| Consumption of agent for test samples [g/m²] | 450 | 420 | 400 | 320 |
| Coeff. of drying speed [%]       | Measured 48.3 % | 56.2 % | 25.0 % | 57.5 % |
|                                  | Standard [4] req. class I: >30 %; class II: >10 % |
| Absorption relation [%]          | Measured 5.9 % | 5.0 % | 18.6 % | 4.0 % |
|                                  | Standard [4] req. < 7.5 % |
| Absorption relation after influence of alkali [%] | Measured 12.4 % | 9.1 % | 36.3 % | 7.9 % |
| Penetration depth [mm]           | Measured 1.5 mm | 4.5 mm | 0 mm | 8 - 9 mm |
|                                  | Standard [4] req. class I: < 10 mm; class II: ≥ 10 mm |

Figure 1. Broken impregnated test specimens. Penetration depth of four various hydrophobic treatment agents. From the left A, B, C, D.
Only agents B and D pass all the normative criteria, see table 1. In addition, the depth of penetration is higher when using these agents (4-6.5 mm for agent B and 8-9 mm for the agent D). Agent A did not pass the test of long-term durability after the test specimens were exposed to alkali effects, most probably due to the small depth of penetration, which was only 1-1.5 mm. Agent C did not pass any of the normative regulations, and no depth of penetration was measured there. When this agent was applied, it formed only a film on the specimen surface.

3. Laboratory test of the effect of agent on the resistance of concrete to frost, water and defrosting salt

Within the wider experimental program, the effect of hydrophobic agent D was tested on the change in the resistance of the concrete against the attack of frost and defrosting salt solution. The result of the test with agent D is presented in the following text. The test was carried out in accordance with Czech standard ČSN 731326 [7] – method C similar to CDF method according specification CEN/TS 12390-9. Test procedure contains 5 mm layer of 3% salt solution on the tested surface. Than the air temperature varies from +5°C (3 hours include temperature change) to -18°C (3 hours include temperature change). The result of the test is the amount of spalled material from the tested surface (see Figure 2). The investor’s requirement for XF4 environment grade is 1000 g/m² spalling of the surface material after 75 cycles of test method C. The surface of the tested concrete samples (cylinders) prepared during the standard production of non-air entraining high strength concrete (HSC) C 70/85 XF4 was used for the comparative test. This concrete was used to produce prestressed bridge beams for a new highway bridge. Oscillation of the compressive strength during production was 90-100 MPa. The results of production tests for this concrete indicated significantly impaired resistance of the concrete to frost attack and defrosting salt attack.

![Figure 2a. Start of the durability test on cores drilled from beams.](image1)

![Figure 2b. Massive surface deterioration (more than 3 kg/m² of spalled material) after 50 cycles of test C according ČSN 731326 [7].](image2)
The degradation found with the high-strength concrete was rather unusual, as there was none of the gradual spalling of individual flakes that is usually found due to the effect of frost and defrosting agents, but series of cracks were found in the structure (see Figure 3).

In order to avoid any impact of surface processing during the production of cylinders (150/300 mm), the resistance test was carried out on the cut surface of the samples. Total 6 disks about 50 mm in height (3 treated + 3 reference) were prepared from three cylinders. Using a brush, agent A was applied to the tested surface of three cylinders. Three layers of agent was applied according to producer recommendation. The total average consumption of the agent on all cylinders was 390 g/m². Three cylinders were used as a reference sample. The test started very soon = 5 days after the agent application. Not as much time was left as is usually required by the suppliers to allow the agent to penetrate into the surface of the concrete.

![Figure 3. Characteristic pattern of cracks on the HSC concrete surface as a result of frost attack. Magnification 15 x.](image)

### Table 2. Result of the frost and defrosting salt attack test - test method C according to ČSN 731326.

| Sample No. | Bulk density [kg/m³] | Surface water absorption 15 min. [g/m²] | Spalling material after freeze thaw cycles [g/m²] |
|------------|----------------------|----------------------------------------|-----------------------------------|
|            |                      |                                        | 25      | 50      | 75      | 100     | 125     |
| 1 – ref    | 2490                 | 164                                    | 300     | 874     | 1594    | 2069    | 2266    |
| 2 - ref    | 2450                 | 98                                     | 344     | 1207    | 1763    | 2282    | 2588    |
| 3 - ref    | 2470                 | 82                                     | 0       | 0       | 0       | 795     | 2007    | 2347    |
| Average    | 2470                 | 115                                    | 215     | 693     | 1384    | 2120    | 2400    |
| 1 - A      | 2480                 | 55                                     | 0       | 0       | 0       | 0       | 16      | 33      |
| 2 - A      | 2540                 | 28                                     | 0       | 0       | 0       | 39      | 189     |
| 3 - A      | 2480                 | 28                                     | 0       | 0       | 0       | 33      | 156     |
| Average    | 2500                 | 37                                     | 0       | 0       | 0       | 30      | 126     |

The results of the durability test were satisfactory and very promising, and the investor decided to use this technology to improve the durability of the beam concrete.
4. Practical application of the hydrophobic agent on bridge beams
Agent type A achieved the best results in the laboratory tests. This agent was chosen for field application to improve the protection of the concrete beams of a six-span beam bridge (see Figure 4). Forty-two precast beams 37,1 m in length were produced from HSC concrete C 70/85 that was not air entrained and was suspected of poor frost resistance.

The field application comprises several steps. First of all, the technology for applying the agent was tested for applying the required amount of the agent (min. 400 g/m² of wet hydrophobic agent). A small field test was arranged in 2010 (May - September), almost 1 year before final application. During the field pre-test, we determined:

- The number of layers needed to apply 400 g/m² of the agent (Figure 5).
- The reference surface water absorption, in order to provide reference information for the control program during final application to the beams (Figure 7).

A reference measurement of surface conductivity, in order to evaluate the quality of the hydrophobic layer (Figure 6).

Figure 4a. Six-span beam bridge = one side of two separate highway bridges. Span 38.33 m.

Figure 4b. Right - cross section of a pre-stressed bridge beam. One span consists of 7 beams.
Figure 5. Pre-test application test to get the required amount of agent on the surface.

Figure 6. Surface conductivity test.

Figure 7. Surface absorption test – Karsten flask.

Afterwards (September 2011 – one year later), the agent was applied on 42 beams (see Figure 8) and control testing (amount, conductivity, surface absorption tests) was also carried out.

Figure 8. Application of the hydrophobic agent on the bridge beams.

The amount of the agent that was applied was controlled by comparing the weight of the applied material with the treated area. Comprehensive results of a surface conductivity test after the agent had been applied are presented in Figure 9.
Figure 9. Comprehensive results of the control conductivity test on the bridge beams. Results on non-treated beams is mentioned as non-treated.

The results of the surface water absorption test (Karsten flask 120 min./200 mm water column) are presented in Table 3.

Table 3. Result of water surface absorption - Karsten flask 120 min./200 mm water column.

| Measured span       | Number of measurements | Mean of surface absorption versus time [min.] | g/m² |
|---------------------|------------------------|---------------------------------------------|------|
| Span 1 – treated    | 3                      | 0                                           | 0    |
| Span 2 – treated    | 2                      | 0                                           | 89   |
| Span 3- treated     | 2                      | 0                                           | 125  |
| Span 4- treated     | 4                      | 0                                           | 122  |
| Span 5- treated     | 4                      | 47                                          | 176  |
| Span 6 – treated    | 3                      | 50                                          | 226  |
| Reference untreated surface | 4 | 0                                           | 354  |

During application of the hydrophobic agent, the control tests showed that:

- The amount of agent that was applied was controlled by comparing the weight of the applied material with the treated area. In this way, it was proved that required amount of 400 g/m² of the hydrophobic agent was applied.
- Comprehensive results of the surface conductivity test after the agent had been applied are presented in Figure 9. Less conductivity with a shallower slope of the graph indicates better results i.e. better agent. It is seen that the application meets the reference values acquired during the field pre-test in 2010, and this was counted as a satisfactory result.
- The reference value for the water surface absorption of the treated surfaces was determined during the pre-test as <350 g/m². Table 3 shows that the control results meet the reference values obtained during the field pre-test in 2010, and this was counted as a satisfactory result.
5. Conclusion
There has been relatively little practical field experience in the Czech Republic with the effect of protecting concrete on the long-term behaviour of hydrophobic impregnations. Our comparative test of the resistance of concrete surfaces has proved that hydrophobic agent has a remarkable positive impact (even unsatisfactory parameters according to EN 1504-2 [4]) on the resistance of the concrete surface against the impact of frost, water, and defrosting salt attack. However, long-term durability and effectiveness is very important when applying hydrophobic agent. Resistance against the impact of weather conditions is mainly related to the ability to penetrate as deep as possible into the structure of the concrete, in order to slow down any degradation of layers caused by weather conditions as much as possible. At the same time, there is a very important effect of an alkaline environment on the resistance of hydrophobic agent against degradation.

The practical application of a hydrophobic agent on the surface of concrete C 70/85, XF4 will provide relevant data on the efficiency of surface treatment with a hydrophobic agent. Treated concrete is five years old after agent application and the bridge structure is now under long-term supervision. Visual inspection of bridge does not show any sign of surface deterioration and concrete defects until now. We are discussing with bridge administrator possibility of surface testing to check reliability and durability of hydrophobic treatment. If the results are satisfactory, we can expect an increased number of applications of surface protection with hydrophobic agents in the Czech Republic.

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References
[1] De Vries J and Polder RB 1997 Hydrophobic Treatment of Concrete Construction and Building Materials 11(4) pp 259-65
[2] Dobiáš D and Kolísko J 2009 Possibilities of hydrophobic treatment of silicate materials Conference - Redevelopment and Reconstruction of Buildings (Brno) pp 37-41
[3] Kolísko J and Hromádko J 2010 Durability of concrete of bridges and tunnels Textbook Highway D8 – concrete constructions
[4] Úřad pro technickou normalizaci, metrologii a státní zkušebnictví (ÚNMZ) 2006 Products and systems for protection and repairs of concrete structures – Definitions, requirements, quality control and conformity assessment – Part 2: Systems of concrete surface protection (ČSN EN 1504-2)
[5] European Committee for Standardization (CEN) 2003 Products and systems for the protection and repair of concrete structures - Test methods - Drying test for hydrophobic agent (EN 13579)
[6] European Committee for Standardization (CEN) 2003 Products and systems for the protection and repair of concrete structures - Test methods - Water absorption and resistance to alkali for hydrophobic agents (EN 13580)
[7] Úřad pro technickou normalizaci, metrologii a státní zkušebnictví (ÚNMZ) 1985 Stanovení odolnosti povrchu cementového betonu proti působení vody a chemických rozmrazovacích látek (Test of concrete against attack of water, frost and defrosting salt) (ČSN 731326)
[8] Pernicova R and Ticha P 2016 Experimental method of measuring the efficiency of hydrophobic surface layer of concrete EAN 2016 - 54th Int. Conf. on Experimental Stress Analysis (Copenhagen)