Quality control of the concrete and corrosion damage of cables of prestressing reinforcement of KA beams, bridge in Chomutov

S Rehacek¹, D Citek¹, M Krystov¹ and J Kolisko¹

¹ Klokner Institute, Czech Technical University in Prague, Solinova 7, Prague 6, Czech Republic

E-mail: stanislav.rehacek@cvut.cz

Abstract. The aim of this paper is to assess the condition of the diagnosed bridge structure, at which previous bridge inspections identified corrosion damage of cables of prestressing reinforcement of KA beams, to assess the extent of corrosion damage of prestressing reinforcement, the condition of chloride ions in concrete of the bearing structure, and to draw up a detailed corrosion assessment of the prestressing reinforcement, then to propose a possible method of the bridge renovation with partial use of new materials (UHPC).

1. Description of the structure
The bridge with the reg. no. 7i-052.1 [1,2,3,4] is a bridge over the Chomutovka Spring. It is a single-span bridge carrying an access ramp to the 1st class road (no. 7) [1]. Bridge abutments and the Caps are made of reinforced concrete. The bearing structure consists of 9 reinforced-concrete prefabricated KA-73 elements. The superstructure is placed on elastomeric bearings.

2. Concrete
2.1. Destructive tests of concrete compression strength
Cored specimens (Ø about 78 and 100 mm) were taken for purposes of destructive tests of concrete compression strength (abutment web, abutment cap and Superstructure). Summary results of the destructive tests of concrete compression strength and corresponding strength classes, or concrete classes, respectively, are stated in the following tables 1 and 2.
Table 1. Summary of results of the concrete compression strength.

| Diagnosed structural elements | Concrete compression strength (MPa) | Variation coefficient ν* |
|------------------------------|-----------------------------------|--------------------------|
| Abutments - web              | destructively 51.2                | 4.7                      |
| Abutments – cap              | destructively 44.8                | 6.4                      |
| Superstructure               | destructively 81.4                | 2.7                      |

* ČSN 73 2011 [3] states a limit value of the variation coefficient for homogeneous concrete of the class C 30/37 and higher: v = 12 % (homogeneity from the viewpoint of strengths).

Table 2. Concrete strength class or concrete class, respectively, on the basis of the tests carried out.

| Diagnosed structural elements | Concrete class / concrete strength class |
|------------------------------|------------------------------------------|
| Abutments - web              | C 40/50, B 250, C 16/20                  |
| Abutments – cap              | C 30/37, B 330, C 25/30                  |
| Superstructure               | At the level C 55/67 – C 60/75, B 330, C 25/30 |

On the basis of destructive tests of concrete compression strength in a very limited range we recommend considering the following concrete classes for the monitored reinforced-concrete structures of the bridge, according to ČSN EN 1992 [5]:
- Abutment web: C 30/37
- Abutment cap: C 25/30
- Superstructure: C 45/55

2.2. Comparison of the concrete carbonation and thickness of the reinforcement cover layer

The concrete carbonation depth was determined evenly along the entire length of the bridge structure. It is possible to estimate the measurement uncertainty within ± 2 mm. Steel reinforcement is exposed to corrosive processes which are affected by a number of factors. The following factors can be considered as the most essential ones:
- Ambient humidity
- Filling of the porous system of concrete with water,
- Depth of placement of the reinforcement under the surface,
- Thickness of the carbonated concrete layer,
- Content of certain pollutants in concrete (chloride ions, presence of acids and other aggressive substances),

If the reinforcement loses its passivation protection due to the concrete alkalinity (carbonation), the presence of humidity calls out corrosion processes leading to known failures, such as dropping out surface layers and reinforcement cross section decrease.

Determination of the thickness of the reinforcement cover layer and concrete carbonation depth was carried out on these elements with the following result:

Substructure
- Concrete carbonation depth: 8 to 20 mm
- Concrete cover of reinforcement: 30 to 45 mm
Superstructure

- Concrete carbonation depth: 1 to 5 mm
- Concrete cover of prestressing reinforcement at the lower surface: 15 to 50 mm
- Concrete cover of stirrups at the lower surface: 0 to 20 mm

2.3. Determination of the content of chlorides in concrete

The content of chloride ions above a certain limit significantly increases the risk of corrosion of the reinforcement. For this reason, a chemical analysis of concrete was carried out within the framework of diagnostic works for the purpose of identification of the content of chloride ions in concrete.

Sampling was distributed evenly along the structure of the bridge. Altogether 30 samples of concrete was taken in 10 sites (always three samples from different heights in one site).

An informative calculation review was carried out under these presumptions and qualified estimations and conditions:

- The quantity of cement used for production of 1 m$^3$ of concrete is 350 kg for the substructure concrete and 420 kg for the concrete of the beams.
- The concrete density was identified from cored specimens and is at a level of 2,340 kg/m$^3$ for concrete used for abutment web and cap, while for the concrete superstructures it is 2,510 kg/m$^3$.

Limit content of Cl$^-$ [% of weight] related to the cement weight is, according to ČSN EN 206+A1 [6], 1 % (of weight) for simple concrete; 0.4 % (of weight) for reinforced concrete; 0.2 % (of weight) for prestressed concrete.

The following can be stated from the carried out chloride content analysis:

- The average content of Cl$^-$ [% of weight] found out by the laboratory analysis for concrete of abutments is 2.24 % for the sampling depth 0-15, 1.97 % for the sampling depth 15-30 and 1.40 % for the sampling depth 30-45 mm. The limit content of Cl$^-$ [% of weight] related to the cement weight is, according to ČSN EN 206+A1, 0.4 % of weight for reinforced concrete.
- The average content of Cl$^-$ [% of weight] found out by the laboratory analysis for concrete of sills is 1.32 % for the sampling depth 0-15, 0.56 % for the sampling depth 15-30 and 0.29 % for the sampling depth 30-45 mm. The limit content of Cl$^-$ [% of weight] related to the cement weight is, according to ČSN EN 206+A1, 0.4 % of weight for reinforced concrete.
- The average content of Cl$^-$ [% of weight] found out by the laboratory analysis for concrete of the superstructure is 0.83 % for the sampling depth 0-15, 0.57 % for the sampling depth 15-30 and 0.46 % for the sampling depth 30-45 mm. The limit content of Cl$^-$ [% of weight] related to the cement weight is, according to ČSN EN 206+A1, 0.2 % of weight for prestressed concrete.

3. Reinforcement of structural elements

3.1. Destructive probes

Altogether 20 destructive probes into the bearing structure and 2 destructive probes into the substructure were made for identification of the reinforcement position.

On the basis of destructive probes carried out and other facts found out it is possible to state in general:

- The probes made into the prestressed beams “KA-73” with a length of 15 m identified prestressing reinforcement in the forms of cables with individual wire diameters 4.5 mm.
- Individual cables with surface corrosion were found in most probes. At the three probes, individual wires were weakened to 3.5 – 4.2 mm. This means weakening of the wire cross section area by more than 40 %. A fully over-corroded cable of prestressing reinforcement was found in one probe.
Sleeves were mostly filled in with an injection mixture. At the two probes the sleeves were not filled in.

The probes made into abutments identified a rebar reinforcing system with a diameter of 24 mm on average. Surface corrosion was found in the place of the probes on the reinforcement.

The probes details are shown in figure 1 and 2.

**Figure 1.** Probe detail, prestressing reinforcement, KA beam, lower face approx. 3.2 metres from the abutment. General decomposition of the prestressing reinforcement.

**Figure 2.** Probe detail, prestressing reinforcement, KA beam, lower face approx. 3.5 metres from the abutment. Heavy or even depth corrosion was found on the prestressing reinforcement. The sleeve was party filled in with injection mixture. Prestressing reinforcement coverage is about 15 mm.
3.2. Corrosion assessment of the prestressing reinforcement

The corrosion survey on the bridge, reg. no. 7i-052.1, included the sampling of corrosion products (very often with fine-grain fragments of the cement injection) and their element analysis by using the XRF method (X-ray fluorescence analysis) and the phase representation analysis by using the XRD method (X-ray diffraction analysis).

On the basis of the probes carried out and other facts found out it is possible to state in general:

- From the results it is clear that corrosion damage was induced and especially stimulated by chloride ions (Cl\textsuperscript{-}), which are components of defrosting salts (NaCl). The content of chloride anions in corrosion products was very important and oscillated between values 1.19 – 3.24 weight %. At the same time, akaganeite (β-FeO(OH)) was found in the corrosion products, containing embedded chlorine atoms, and also generally significant quantity of hydrocalumite (hydration phase of cement containing chlorine atoms) was found in injection residuals.

- From the results it is clear that at cables it is possible to register highly localised and unpredictable corrosion damage stimulated by chloride anions. Localisation is given mainly by penetration of humidity into the area of the routing of prestressing reinforcement (leakage, condensing). The injection system was originally modified by using finely ground limestone in a rheological way.

- The result from one of the sample is shown in table 3 and figures 3 and 4.

**Table 3.** Results of the XRF element analysis of the corrosion products sampled from the A1 sampling site.

| Element | Representation [weight %] |
|---------|--------------------------|
| Na      | 1.28                     |
| Mg      | 1.38                     |
| Al      | 3.40                     |
| Si      | 11.50                    |
| S       | 1.11                     |
| P       | 0.04                     |
| Ca      | 41.69                    |
| Cl      | 2.71                     |
| Fe      | 35.89                    |

**Figure 3.** Diffraction pattern of corrosion products sampled from the A1 sampling site.
| Phase name      | Chemical formula | Representation [semi-quant %] |
|-----------------|------------------|-----------------------------|
| Calcite         | CaCO₃            | 41                          |
| Ettringite      | CaₓAlᵧSₓOₓHₓ     | 22                          |
| Hydrocalumite   | CaₓAlₓCₓOₓClₓHₓ  | 13                          |
| Quartz          | SiO₂             | 5                           |
| Magnetite       | Fe₃O₄            | 7                           |
| Goethite        | α-FeO(OH)        | 6                           |
| Lepidocrocite   | B-FeO(OH)        | 5                           |

_Figure 4._ Legend to the diffraction pattern from _Figure 3._

4. **Summary and conclusions**

- Because of the limited number of destructive tests of concrete compression strength we recommend consideration of the concrete class:
  - Abutment web: C 30/37
  - Abutment cap: C 25/30
  - Superstructure: C 45/55

- While comparing the cover layer of concrete and the carbonation depth found out it is clear that a part of the diagnosed reinforcement (stirrups on the lower face of the beams) is already situated in the carbonated concrete layer and is not protected from corrosion with its natural alkalinity anymore. The beam stirrups are locally fully exposed and over-corroded. The same holds for cables of the prestressing reinforcement of the beams where the concrete cover layer has fallen off and the actual prestressing reinforcement has been exposed due to the influence of expansion corrosion pressures. Especially edge beams.

- The content of chloride ions in the substructure concrete is high in the entire range of the sampling depth (0 – 45 mm) and does not meet requirements of ČSN EN 206+A1. The content of chloride ions is within the standard limits only in the depth range of 30 – 45 mm at abutment sills.

- The content of chloride ions in the superstructure concrete in the range of the sampling depth (0 – 45 mm) is high and does not meet requirements of ČSN EN 206+A1.

- Individual cables with surface corrosion were found in the place of destructive probes to the prestressing reinforcement of the KA beams. At three probes, individual wires were weakened to 3.5 – 4.2 mm. This means the weakening of the wire cross section area by more than 40 %. A fully over-corroded cable of the prestressing reinforcement was found in one probe.

- The sleeves were mostly filled in with an injection mixture. At two probes the sleeve was not filled in.

- From the results of the corrosion survey of the prestressing reinforcement it is clear that corrosion damage was induced and especially stimulated by chloride anions (Cl⁻), which are components of defrosting salts (NaCl). The content of chloride anions in corrosion products was very important and oscillated between values 1.19 – 3.24 weight %. At the same time, akaganeite (β-FeO(OH)) was found in the corrosion products, containing embedded chlorine atoms, and also generally significant quantity of hydrocalumite (hydration phase of cement containing chlorine atoms) was found in injection residuals.
From the results it is clear that at cables it is possible to register highly localised and unpredictable corrosion damage stimulated by chloride anions. Localisation is given mainly by penetration of humidity into the area of the routing of prestressing reinforcement (leakage, condensing). The injection system was originally modified by using finely ground limestone in a rheological way.

On the basis of the facts found out, the superstructure correspond to the building state V according to ČSN 73 6221 – poor condition = The defects and failures have a principal influence on reliability of the structure and are removable only through major interventions into the superstructure.

It implies from the results of the corrosion survey that the beams are approaching the end of their lifetime due to the long-term leakage of salty solutions into the structure and effects of other corrosion factors from the viewpoint of durability. It is only possible to remove the identified defects of the superstructure by replacing the superstructure with a new one. With regard to the defects found, we recommend execution of replacement of the superstructure with the new one not later than within 5 years.

Acknowledgments
This article was written with kind contribution of the project SGS19/139/OHK1/2T/31.

References
[1] Listing from the BMS system (Bridge management system)
[2] Archive documentation, digital copies of longitudinal and cross sections, 5/1983. Supplied by the Client
[3] Type ground documents concerning the KA-73 prefabricated beams, Dopravoprojekt 11/1973, digital copies
[4] ČSN 73 6221 Inspection of Road Bridges
[5] ČSN EN 1992: Eurocode 2: Design of concrete structures
[6] ČSN EN 206+A1: Concrete - Specification, performance, production and conformity