Corrosion-inhibiting systems for concrete bridges
Cusson, D.; Qian, S. Y.

Publisher's version / Version de l'éditeur:

Construction Canada, 49, March 2, pp. 26-28, 30, 32, 2007-03-01

Corrosion-inhibiting systems for concrete bridges

NRCC-49255

Cusson, D.; Qian, S.

A version of this document is published in / Une version de ce document se trouve dans:
Construction Canada, v. 49, no. 2, March 2007, pp. 26-28, 30, 32

Evaluation of Corrosion-Inhibiting Systems on a Concrete Bridge Deck

By Dr. Daniel Cusson and Dr. Shiyuan Qian

Introduction

Keeping Canada's highway bridges in good condition is crucial to economic productivity and public safety. This is a challenging problem in areas where de-icing salts are used. While de-icing salts vastly increase the safety of winter road travel, they are the main cause of deterioration of reinforced concrete structures, including bridges.

Corrosion inhibitors are one means among many to protect concrete reinforcement from corrosion. There are many corrosion-inhibiting systems commercially available, including inorganic and organic concrete admixtures, rebar coatings, and coatings applied to the concrete surface. Although these products have been considered cost-effective for prolonging infrastructure life, a lack of information about their long-term performance has made it difficult for engineers and bridge owners to select appropriate corrosion inhibitors for both new construction and rehabilitation projects.

For the past ten years, the National Research Council Institute for Research in Construction (NRC-IRC) has been studying the effectiveness of several commercially available products designed to extend the service life of concrete structures by delaying the corrosion of reinforcing steel. The researchers monitored the performance of nine corrosion-inhibiting systems applied on sections of a major highway bridge in Laval, Québec (Figure 1). The main objective of the investigation was to identify the most effective corrosion-inhibiting systems under severe environmental conditions that are typical of cold regions of Canada.

The Research Project

The Vachon Bridge is a six-lane structure with a 714-m total length. It has 21 spans of prestressed concrete girders supporting a reinforced concrete deck. The opportunity for the research arose in 1996 when *Transports Québec* was undertaking a major rehabilitation of the bridge, including the rebuilding of the barrier walls. The Ministry and NRC-IRC worked out a collaborative project in which ten consecutive 34-m spans of the east-side barrier wall were selected for the testing of nine corrosion-inhibiting systems (Table 1). The same basic concrete mix was used for the ten test sections of barrier walls.

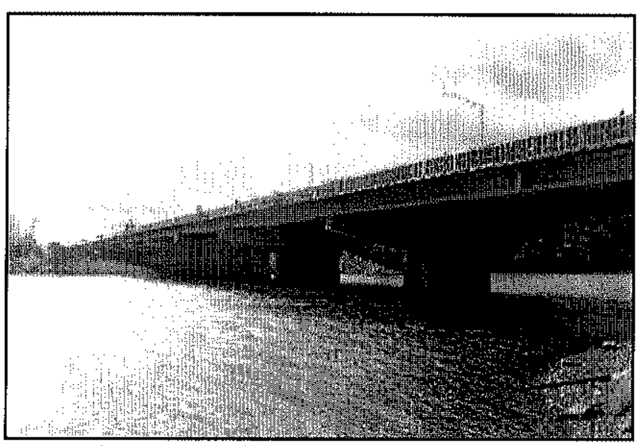

Figure 1. Vachon Bridge, Laval, Québec

For purposes of comparison, two of the test spans were rebuilt with no corrosion inhibitors: one had carbon-steel reinforcement (identified as Control in Table 1), and the other had epoxy-coated steel reinforcement (identified as Epoxy in Table 1). The eight other test spans (conventional carbon-steel reinforcement, 15M bars), each had a different corrosion inhibiting system (A to H, Table 1), provided and installed by the product manufacturer.

The concrete used for the reconstruction of the test sections had a water-cement ratio of 0.36, a cement content of 450 kg/m^3 and an average 28-day compressive strength of 45 MPa. Placement occurred over a seven-day period in October 1996.

Table 1. Description of the barrier wall test sections

Test Span	Description †
Control	Carbon-steel reinforcement
Epoxy	Epoxy-coated steel reinforcement
A	Rebar coating (water-based liquid blend, Portland cement and fine silica sand); Concrete coating (polymer-based liquid blend, Portland cement and aggregates)
B	Organic concrete admixture (alkanolamines); Coating only on anchor rebars from slab (water-based epoxy, Portland cement)
C	Organic/inorganic concrete admixture (amine derivatives, sodium nitrite)
D	Rebar coating (water-based epoxy, cementitious components)
E	Organic concrete admixture (amines and esters)
F	Organic concrete admixture (amines and their salts with organic/inorganic acids)
G	Organic concrete admixture (alkanolamines, ethanolamine and phosphate); Coating only on anchor rebars from slab (water-based epoxy, Portland cement); Concrete sealer (water-repellent penetrating silane)
H	Inorganic concrete admixture (calcium nitrite)

† Commercial names are not identified to maintain the anonymity of the manufacturers, as requested.

To enable an early evaluation of the performance of the test systems, two sets of rebar ladders were embedded in each test span (Figure 2a). Each ladder was made up of four 10M horizontal bars, installed in the barrier wall to provide concrete cover thicknesses of 13 mm for the upper bar (Bar #1), and 25 mm, 38 mm and 50 mm for the other three bars (Figure 2b).

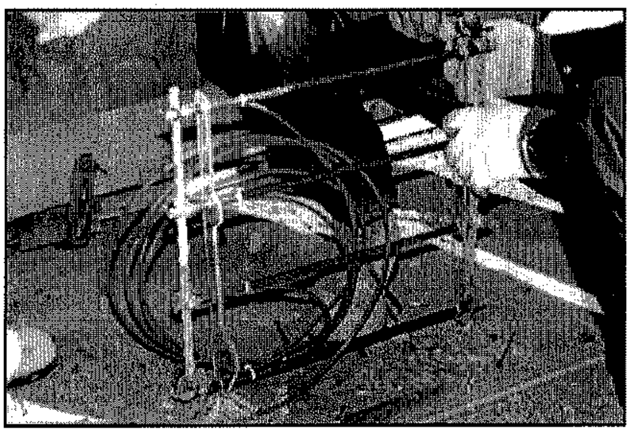

Figure 2a. Rebar ladder being prepared before installation in formwork.

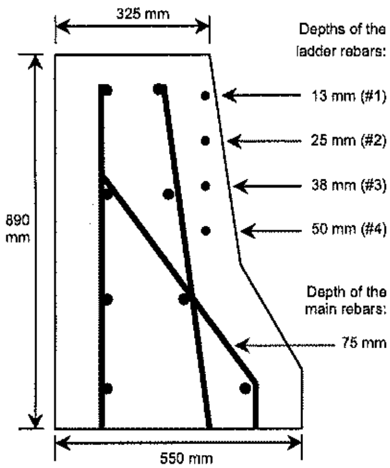

Figure 2b. Cross-section of barrier wall showing the main reinforcement with transverse bars spaced at 230 mm, and a test rebar ladder to the right.

A visual inspection of the barrier wall a few days after casting revealed closely spaced vertical cracks running through the walls (Figure 3). The cracks were 800 mm apart on average and less than 0.3 mm in width. It was determined that this cracking was mainly due to uncontrolled thermal effects and autogenous shrinkage, typical of concrete with high cement content and low water-cement ratio.

During the ten years of the study, the measured temperature in the barrier wall typically varied from –15°C in January to +35°C in August. The relative humidity (RH) in the wall reached the highest values in May-June (frequent rainy periods) and the lowest values in December-January (cold and dry periods). After ten years, the RH in the concrete decreased from 100% to about 80%.

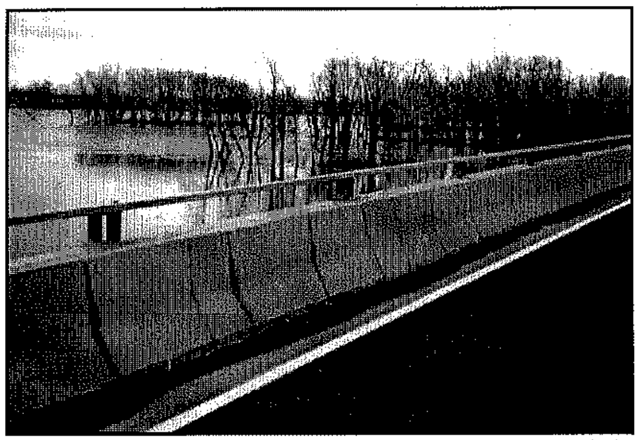

Figure 3. Typical span of the barrier wall showing early-age shrinkage cracks

Data Collection and Analysis

Both visual inspection and measurements (annually in May or June from 1997 to 2006) and periodic core sampling (May 1997, June 2001 and June 2006) were carried out to assess the effectiveness of the corrosion-inhibiting systems.

Core sampling

Cores were taken from the barrier wall to measure key concrete properties such as compressive strength, coefficient of permeability, and chloride content (an indicator of the risk of initiation of corrosion).

It was found that the compressive strength increased in the first four years, from 45 to 61 MPa on average, with no significant change thereafter. In 1997, the coefficients of permeability were considered moderate, while those measured in 2001 and later were very low. This improvement was most likely the result of continued cement hydration. The corrosion-inhibiting systems did not appear to have any detrimental effects on either of these concrete properties.

The chloride contents periodically measured in the barrier wall are shown in Figure 4. In general, chloride contents increased over time and decreased with cover depth, as expected. By 2001, the chloride contents at a depth of 13-25 mm in all test spans exceeded the critical value of 0.1%, above which chlorides may initiate corrosion of the reinforcement. (This critical chloride value is approximate only and is likely higher for concretes containing corrosion inhibitors.)

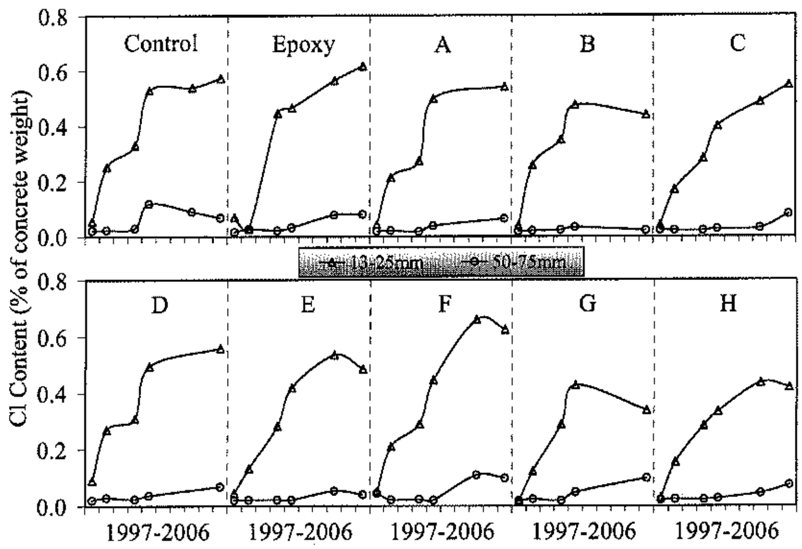

Figure 4. Total chloride content (from core samples)

By 2006, the chloride contents at depths of 50-75 mm in all test sections were still below the critical value of 0.1%. This suggests that the risk of corrosion of the main reinforcement was low in areas where the initial cracking was not present. The system in Span G performed very well in 1997, at which time no chlorides had penetrated into the concrete. This was due to the protective sealer applied to the concrete surface. In the following years, chlorides penetrated into the concrete of Span G but at a lower rate than in the other systems tested.

Corrosion of the rebar ladders

The annual inspections included measurements of half-cell potential (an indicator of the risk of corrosion) at 110, 345 and 550 mm from the top of the barrier wall, and horizontally at 300-mm intervals along the central 15 metres of each span. In addition, measurements of the current density (an indicator of the rate of corrosion) were taken on vertical and horizontal bars at cracked and uncracked locations in each test span.

The barrier wall surface was visually inspected in June 2006 for corrosion-induced damage over Bar #1 (concrete cover 13 mm, Figure 2b) of each test ladder. After ten years, corrosion had become evident in the region of Bar #1 in each test span. Test sections D and H had the lowest degree of damage with only minor horizontal cracks over these rebars. Sections A, C, E and F had horizontal cracking, small delaminations and spalled areas near these rebars.

Concrete cores over Bar #2 (25 mm concrete cover, Figure 2b) were taken in June 2006 from the test ladders. The rust observed at the steel surface had not progressed significantly on these bars by this time. Another set of cores was taken in June 2006 over the main reinforcement (75 mm cover) of the barrier wall. Their locations were chosen to correspond to places where readings indicated the most negative half-cell potentials and the highest corrosion rates. The results from the core sampling indicated that the main reinforcement showed no significant active corrosion, which can be attributed to the substantial depth of the concrete cover (75 mm) and the very low permeability of the concrete.

Figure 5 shows the half-cell potential measured non-destructively on Bars #1 and #2 in the test rebar ladders. For all the test spans, the half-cell potential started at a value near –200 mV and decreased with time. There was a higher risk of corrosion at Bar #1 (13 mm cover) because of a higher chloride content at that bar. The curves in Figure 5 also show that Spans F and H had the least negative potentials (i.e. lowest risks of corrosion) at a depth of 25 mm (Bar #2) compared to the other test sections.

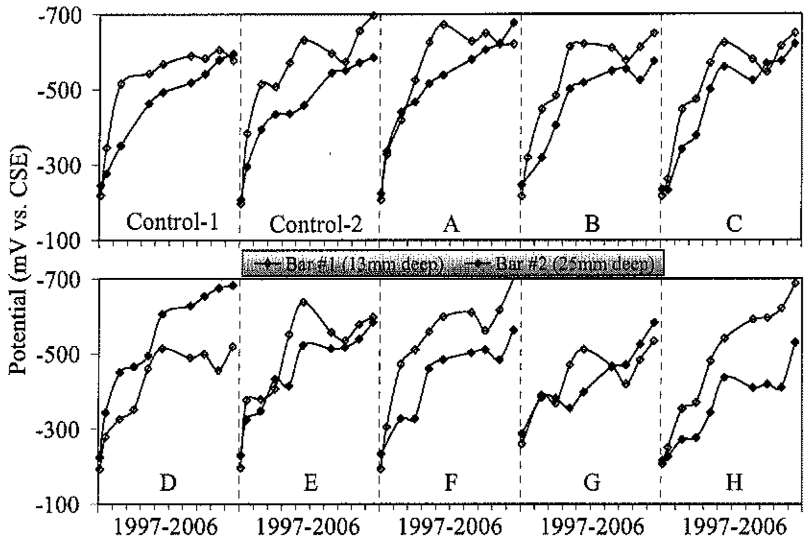

Figure 5. Half-cell potential measured over test rebar ladders
(more negative values indicate higher risks of corrosion)

Figure 6 shows the current density (indicator of the rate of corrosion) measured on the test rebar ladders for each span. In general, the corrosion rates were much higher for Bar #1 (13 mm cover) than for Bar #2 (25 mm cover). In 2006, all corrosion rates on Bar #1 exceeded the critical value of 0.5 $\mu A/cm^2$, indicating active corrosion. This is consistent with the actual damage to the concrete observed over Bar #1 of the rebar ladders. The curves of the corrosion rate at Bar #2 show that test spans H and B had the lowest rates in 2006 compared to the control span and the other systems. Spans E and F also had low corrosion rates.

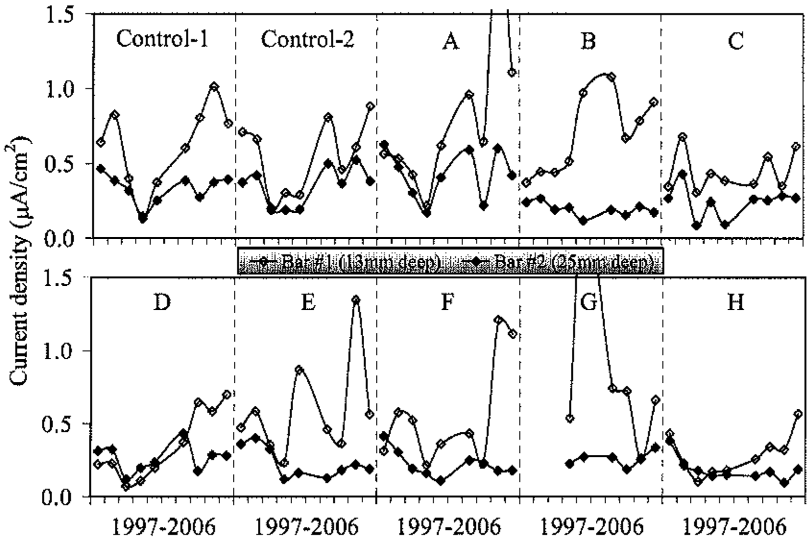

Figure 6. Corrosion rate measured over test rebar ladders.

Corrosion of the main reinforcement

Initially (1997 and 1998), the main reinforcement (75 mm cover) in the test spans with no coatings on the rebars developed relatively high oxidation currents owing to the normal formation of a protective oxide film on the steel and the high moisture content in the new concrete. Thereafter, the corrosion rates decreased in all test spans (due to the protective action of the oxide film, and drying) towards values below the critical value of 0.5 $\mu A/cm^2$. At this level, corrosion is not considered to be active. In general, higher corrosion rates were found at cracked locations than at uncracked locations (as expected).

Summary and Conclusions

The field performance of the corrosion-inhibiting systems was evaluated mainly from corrosion risk and corrosion rate measurements and from inspections of the concrete surface and cored reinforcing bars.

The non-destructive evaluation of corrosion over the main reinforcement (75 mm cover) indicated that the risk of corrosion in all test spans was still low after ten years of service, but increasing at a low rate. However, the corrosion-inhibiting systems used in this study provided a second line of defence in the event that the concrete cover was breached because of cracking.

The major findings of the study can be summarized as follows:

- Concrete core testing indicated the concrete was of very good quality, with a very low permeability and a compressive strength exceeding its 35 MPa design requirement.
- Total chloride contents measured after 10 years at depths of 50-75 mm remained below or near the critical chloride value of 0.1% in all test spans. This suggests that the risk of corrosion of the 75-mm deep reinforcement remained low at uncracked locations.
- The concrete sealer of Span G performed very well during the first year, at which time a negligible amount of chlorides had penetrated into the concrete. In the following years, chlorides penetrated into the concrete of Span G but at a lower rate than in the other systems that had no sealer applied to the concrete surface.
- Corrosion-induced damage of the barrier wall surface over Bar #1 (13 mm cover) of the test ladders was observed in all test spans, with the least damage occurring on Spans D and H (minor cracks).
- Concrete cores that sampled Bar #2 (25 mm cover) of the test ladders and the 75-mm deep main reinforcing bars indicated no clear evidence of active corrosion in any of the test spans. This is due to the very good quality of the concrete used in the construction of the barrier wall (i.e. very low water permeability).
- Corrosion rates on the main reinforcement measured over the vertical shrinkage cracks (which appeared shortly after construction) were consistently higher than those measured over uncracked locations, regardless of the corrosion-inhibiting system used, including the system with epoxy-coated reinforcement.

Of the corrosion-inhibiting systems tested, the one in Span H (inorganic concrete admixture) consistently provided the best performance, followed by those in Spans B, E and F (organic concrete admixtures). The epoxy-coating system also performed well, but was showing signs of decreasing performance over time.

The lack of significant active corrosion on the main reinforcement in either the corrosion-inhibiting systems or the control span highlights the importance and benefits of low permeability concrete and adequate thickness of the concrete cover over the reinforcement.

Dr. Daniel Cusson and Dr. Shiyuan Qian are research officers in the Urban Infrastructure program of the National Research Council Institute for Research in Construction.