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Inhibiting Chloride-Induced Corrosion in Concrete Bridges

By Daniel Cusson and Shiyuan Qian

The use of de-icing salts can significantly reduce the service life of concrete transportation structures by causing corrosion of the reinforcing steel. This Update provides guidance on controlling corrosion, drawing on a ten-year study to assess the performance of eight commercial corrosion-inhibiting systems on a concrete highway bridge.

The use of de-icing salts is crucial to safe winter travel in cold climates, but it can lead to premature corrosion of the reinforcing steel in concrete. Typically, chloride ions from de-icing salts mixed with moisture can penetrate concrete through pores and cracks, accumulate near the reinforcing steel, and initiate corrosion. Corrosion that develops around the reinforcing steel can generate more pressure in the concrete and possibly initiate additional cracks, weakening the structure and reducing its durability. The practical consequence of this is that billions of dollars¹ are spent each year in North America to repair structures such as bridges and parking garages that are exposed to these salts.

A number of technologies have been developed and used to control or delay corrosion. One is the use of a corrosion-inhibiting system. There are many such systems available: rebar coatings, inorganic and organic admixtures, and coatings applied to the concrete surface. Although corrosion inhibitors have been used over the past 20 years, the scarcity of scientific information about their field performance has made it difficult to specify appropriate products.

During a ten-year period, researchers at the National Research Council Institute for Research in Construction (NRC-IRC) studied the effectiveness of eight commercially available corrosion-inhibiting systems on



Figure 1. Vachon Bridge during rehabilitation in 1996, Laval, Québec

the Vachon Bridge in Laval, Québec (Figure 1). The bridge is a 6-lane, 714-m long structure with 21 spans of prestressed concrete girders supporting a reinforced concrete slab. In 1996, Transports Québec undertook a major rehabilitation of the bridge including a rebuilding of the barrier walls.

NRC-IRC and Transports Québec saw the bridge rehabilitation project as an opportunity to conduct a comprehensive investigation of corrosion inhibiting systems. Concrete barrier walls were selected as the focus of the study because of their high exposure to de-icing salts and their accessibility for carrying out measurements to determine the level of corrosion that developed over the ten-year period.

Table 1. Description of corrosion-inhibiting systems installed in barrier wall test sections

Test Section	Description [†]	Corrosion Inhibition Mechanism
A	<ul style="list-style-type: none"> Rebar coating (water-based liquid blend, Portland cement and fine silica sand) Concrete coating (polymer-based liquid blend, Portland cement and aggregates) 	Acts as a physical barrier to reduce migration of chloride ions to the reinforcing steel.
B	<ul style="list-style-type: none"> Organic concrete admixture (alkanolamines) Coating only on anchor rebars from slab (water-based epoxy, Portland cement) 	Blocks electrochemical reactions by depositing a physical protective layer on the reinforcing steel.
C	<ul style="list-style-type: none"> Organic/inorganic concrete admixture (amine derivatives, sodium nitrite) 	Stabilizes the passive oxide layer ^{††} on the reinforcing steel. Reduces the mobility of chloride ions by increasing the density of the concrete.
D	<ul style="list-style-type: none"> Rebar coating (water-based epoxy, cementitious components) 	Acts as a physical barrier to reduce penetration of chloride ions to the reinforcing steel.
E	<ul style="list-style-type: none"> Organic concrete admixture (amines and esters) 	Promotes the formation of a physical barrier to chloride ions on reinforcing steel and reduces concrete permeability.
F	<ul style="list-style-type: none"> Organic concrete admixture (amines and their salts with organic/inorganic acids) 	Migrates in concrete and adsorbs on steel surface to form a film blocking electrochemical reactions.
G	<ul style="list-style-type: none"> 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) 	Blocks electrochemical reactions by depositing a physical protective layer on the reinforcing steel.
H	<ul style="list-style-type: none"> Inorganic concrete admixture (calcium nitrite) 	Enhances the passive oxide layer ^{††} of the steel reinforcement, and reacts with anodic corrosion products competing with chloride ions.
Control	<ul style="list-style-type: none"> Carbon-steel reinforcement No corrosion inhibitor 	Not applicable
Epoxy	<ul style="list-style-type: none"> Epoxy-coated reinforcement No corrosion inhibitor 	Not applicable

[†] Commercial names are not identified to maintain the anonymity of the manufacturers, as requested.
^{††} The passive layer is the initial oxidation product that forms on uncoated reinforcing steel due to availability of moisture and oxygen. Once formed, this layer, which is sustained by the high alkaline environment in concrete, can protect the steel from corroding further.

The study was considered representative of any reinforced concrete structure exposed to de-icing salts and to harsh climate conditions, which included temperatures ranging from -25°C (-15°F) to 35°C (95°F) and repeated freeze/thaw cycles and wet/dry cycles.

Ten consecutive 34-m test sections of the east-side barrier wall were selected for the study. Eight of the test sections were built using the same basic concrete mix design and conventional carbon-steel reinforcement (15M bars). The concrete mix had a water-cement ratio of 0.36, and a cement content of 450 kg/m³ (760 lb/yd³) (CSA Type GU, similar to ASTM Type I), resulting in a 28-day compressive strength exceeding the required 35 MPa. In each of the eight test

sections, a different corrosion-inhibiting system was installed by the manufacturers (A to H, Table 1).

The other two test sections were built without a corrosion-inhibiting system: one section had carbon-steel reinforcement (Control, Table 1), and the other had epoxy-coated steel reinforcement (Epoxy, Table 1).

To detect corrosion early, two sets of 10M rebar ladders were embedded in each test section during construction (Figure 2) with concrete covers varying from 13 mm to 50 mm. The main reinforcement in the barrier wall had a concrete cover of 75 mm.

Vertical cracks about 800 mm apart appeared on the barrier walls several days after concrete placement (Figure 3). It was determined that the cracking was mainly due to uncontrolled thermal effects and

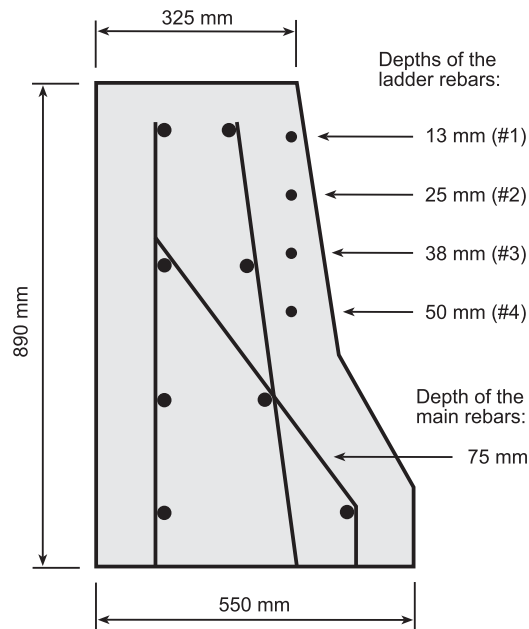


Figure 2. Dimensions and reinforcement details of barrier wall showing main reinforcement with transverse bars spaced at 230 mm, and a test rebar ladder to the right.

Data Collection

Annual assessment of corrosion in concrete barrier wall sections included:

- Measurement of half-cell potential (an indicator of *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-m portion of each section.
- Measurement of the corrosion current density by the linear polarization method (an indicator of *rate of corrosion*) at selected vertical and horizontal bars at cracked and uncracked locations in each test section.
- Core sampling to measure chloride concentration, permeability and strength of concrete in each test section.

restrained autogenous shrinkage, typical of concrete with high cement content and low water-cement ratio. It was decided to proceed with the study and to monitor the effect of early cracking on corrosion.

Results

Penetration of chlorides into concrete

In general, the chloride content in the concrete barrier wall increased over time and decreased with cover depth, as expected. By 2001 (Year 5), the total chloride contents at a depth of 13 to 25 mm in all test sections significantly exceeded the commonly used critical value² of 1.4 kg/m³, above which



Figure 3. Typical span of barrier wall after reconstruction.

chlorides may initiate corrosion of the reinforcement. (Note: The threshold value of critical chloride content varies depending on several parameters, including: type of reinforcing steel, concrete mix design, carbonation and the environmental conditions. Concretes containing corrosion inhibitors can likely tolerate higher critical values before the onset of corrosion.)

By 2006 (Year 10), the chloride contents at a depth of 50 to 75 mm in all test sections were near but below the critical threshold value, suggesting that initiation of corrosion at the main reinforcement was just about to start at locations where there were no cracks in the concrete.

The corrosion inhibiting system in Section G, however, performed very well. By 1997, no chlorides had penetrated the concrete, owing to the fact that a water-repellent sealer (applied to the surface of the barrier wall) was part of this system. In the following years, chlorides penetrated the concrete in Section G but at a lower rate than in the other sections.

Corrosion of the rebar ladders

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

Concrete cores that sampled Bar #2 (25 mm concrete cover) were taken in June 2006 from each test ladder. Although the presence of chlorides at Bar #2 in 2001 indicated that corrosion could be imminent for some of the test sections, the appearance of the steel surface had not changed significantly by 2006.

Corrosion of the main reinforcement

Initially, in 1997 and 1998, the main reinforcement (75 mm cover) in the test spans with no coatings on rebars showed relatively high corrosion rates owing to the normal formation of a protective oxide film on the steel (see second footnote in Table 1). Thereafter, the corrosion rates decreased in all spans towards values below the critical value of 0.5 $\mu\text{A}/\text{cm}^2$ (the indicator of rate of corrosion) at which corrosion is not considered to be active. In general, higher corrosion rates were found at cracked locations than at locations without cracks, with an average increase of 35% for the nine spans that did not have epoxy coated rebars.

Another set of cores was taken in June 2006 over the main reinforcement (75 mm cover). The locations of the cores were chosen to correspond to the places where non-destructive measurements indicated more negative half-cell potentials (i.e. highest possible risk of corrosion) and higher corrosion rates. Regardless, the main reinforcement showed no significant active corrosion, including the control sections, which can be attributed to the substantial concrete cover (75 mm) and the very low permeability of the concrete.

Conclusions

This study evaluated the field performance of eight corrosion-inhibiting systems installed on a reconstructed bridge barrier wall over ten years. The following conclusions were found:

1. Of the corrosion inhibiting systems tested, System H (calcium nitrite admixture) consistently provided the best performance in the field by enhancing the passive oxide layer which protects reinforcement against corrosion.
2. System G (migrating sealer) performed very well during the first year by blocking chlorides from penetrating into the barrier wall. In the following years, chlorides penetrated the concrete cover but at a lower rate than in other sections where a surface sealer was not used.

3. Corrosion rates on the main reinforcement over the vertical cracks that developed soon after placement were consistently higher than those measured over uncracked locations, regardless of the corrosion-inhibiting systems used (including the system with epoxy-coated reinforcement). This finding highlights the importance of controlling cracking and minimizing crack width in concrete.
4. The use of a thick concrete cover made of low permeability concrete keeps the reinforcement well protected against de-icing salt attack.

The first line of defence against corrosion of steel reinforcement in concrete structures exposed to de-icing salts is the quality and thickness of the concrete cover, as prescribed in design codes. The corrosion-inhibiting systems used in this study should be regarded as a second line of defence. When concrete cracks, the first line of defence is weakened and the second becomes particularly important.

Detailed results may be examined by reviewing the research reports posted at: <http://www.nrc-cnrc.gc.ca/eng/projects/irc/corrosion-inhibiting.html>

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