# CORROSION AND KANSAS BRIDGES

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Kansas, like other snow-belt areas, has experienced increased corrosion of bridge deck reinforcing and structural steel as the use of de-icing salts has increased. Spalls and hollow planes in the concrete deck form in areas of shallow steel as a result of the corrosion. Some localized small hollow planes, however, are associated with reactive aggregates and also speed up the corrosion process. The copper-copper sulfate half-cell potential detection method has been found useful to predict future hollow plane or spall development related to corroding reinforcing steel. Even new bridges may show a small amount of active corrosion as measured with the half-cell equipment. Much structural steel corrosion seems to be related to the quality of workmanship in preparation and painting and to de-icing salts rather than to the quality of the paint. Steel girders have been observed to act as sacrificial anodes, forming magnetite as they corroded but protecting the reinforcing steel from corrosion. The concrete deteriorated anyway and had to be removed and recast. Concrete deterioration associated with the corrosion of reinforcing steel can be reduced or delayed by increasing the depth of cover over the top reinforcement. Structural steel corrosion can be reduced by proper preparation and quality inspection during painting operations. Carrying salty meltwater away from the steel will also help.

•BRIDGE DECK deterioration has been studied in Kansas for many years. During this time several facets of corrosion problems associated with bridge steel have been observed. This is a report of some of those observations.

The increased use of chloride de-icing salts since the mid-50s has aggravated the problem of bridge steel corrosion and brought about an earlier onset of deterioration in some structures. Bridge corrosion problems are primarily of 2 major types. One is associated with corrosion of the concrete reinforcing steel, and the other is associated with corrosion of the structural steel. Each of these problems has several variations that increase the difficulty of control.

## CORROSION OF REINFORCING STEEL

Corrosion of the reinforcing steel has been cited by many investigators ($\underline{3}$, $\underline{6}$, $\underline{9}$, $\underline{11}$, $\underline{12}$) as the single most important probable cause of the development of hollow planes or delaminations and spalls in bridge decks. In Kansas, we have investigated the effect of depth of cover on preventing or delaying the onset of corrosion ($\underline{1}$, $\underline{5}$).

### Depth Studies

Figures 1 and 2 show the depth of the reinforcing steel as measured by a pachometer on a 14-year-old Kansas bridge ($\underline{5}$, $\underline{8}$). The 20- by 26-ft (6.10- by 7.92-m) section of the deck shows extensive hollow plane and spall deterioration areas related to steel that is generally less than $1\frac{1}{2}$ in. (38.1 mm) deep, and much of it less than 1 in. (25.4 mm) deep (Fig. 1). Figure 2 shows a similar-sized area of the deck where there is little deterioration and the steel is generally more than $1\frac{1}{2}$ in. (38.1 mm) deep, and

**Figure 1. Reinforcing steel pattern, depths, and types of damage on a 20-ft section of deck.**



**Figure 2. Isolated hollow planes in an area where steel is primarily deeper than 1½ in. (38.1 mm).**

much of it more than 2 in. (50.8 mm) deep. Most of the hollow areas shown in Figure 2 are related to expansive chert aggregate particles, and the plane of cleavage is above the reinforcing steel (5).

Figure 3 shows more clearly the relation between the depth of the reinforcing steel and the amount of deterioration on the bridge deck. With passing time more deterioration occurred, and the percentage associated with deeper steel increased but not nearly so rapidly as with shallower steel. The 16-year curve shown in Figure 3 represents the deck surface area actually removed for repair purposes when a 2-in. (50.8-mm) bonded portland cement concrete overlay was placed on the deck (5). This figure shows the importance of placing the steel as deep as possible. Where the average steel depth was 2 in. (50.8 mm) on this deck, only 8 percent of the area was associated with deterioration after 16 years. Nearly all of that was related to expansive chert aggregate or to $1^{1}/_{2}$-in. (38.1-mm) deep steel. Even though the average steel depth in this area of the bridge is 2 in. (50.8 mm), the normal distribution of variation in depth provided about 8 percent of the steel with a cover of $1^{1}/_{2}$ in. (38.1 mm) or less. A cover of 3 in. (76.2 mm) rather than 2 in. (50.8 mm) over the steel on a properly designed deck with concrete of higher cement content and lower water-cement ratio than commonly used should provide many more years of protection (2).

## Corrosion Activity Measurements

Field measurement of corrosion activity was made by the Cu-CuSO$_4$ half-cell method (11) on a number of bridges and predicted coming problems. One bridge, described in our final bridge deck report (2), showed no visible damage. A chain sweep found no hollow planes. This bridge was being evaluated in a special research study so that we had yearly data on the deck. The Region 15 Corrosion Device Demonstration Team of the Federal Highway Administration checked the bridge, and the half-cell measurements showed active corrosion (0.35 V or greater) in one area. New inspections and chain sweeps still revealed no damage. About 1 year later, when the bridge was 11 years old, spalls and hollow planes developed in the area of active corrosion. New half-cell measurements showed potentials even higher than those of the previous year. This deck also had a few small hollow areas that developed where there was no active corrosion of the steel. These were determined to be due to large reactive aggregate particles; the plane was above the reinforcing steel.

Another bridge that was overlaid with 2 in. (50.8 mm) of concrete was checked for corrosion potential. The first survey, which was made about 1 year after overlay construction, showed 6 percent of the deck to have a reading of 0.35 V or greater. Two years later, the reading was 9 percent. This indicates that even with the new concrete cover corrosion continues. The added concrete cover, however, should be an aid in keeping the progress of corrosion damage to a minimum.

To follow the corrosion history of some of our bridges, we have begun a study of new bridges. Eight newly constructed bridges were tested for corrosion potential before they were opened to traffic or de-icing salts were used on them. The results are given in Table 1. The tests show that even new decks may have corrosion potentials in the active region. Four of these 8 showed active potentials. Most of the higher values were at the bridge ends, which are places of high readings in older decks. The new bridges are a part of the primary road system and are subject to moderate to heavy applications of de-icing salts. We plan to resurvey these bridges each year and are not sure that covering those that show active corrosion potentials with a membrane would be beneficial.

Corrosion potential surveys were made on a statistical sample of bridges as old as 15 years and now in service; data are given in Table 2. In general, the older decks have somewhat higher potential values than the younger ones, but all decks of the same age do not have similar percentages of high corrosion potentials. Data given in Table 1 indicate that some new bridges also have high readings. The 15 in-service bridges have had de-icing salts used on them and carry primary road system traffic. Bridges of the same age have had about the same amount of de-icing salts applied. Detailed steel depth measurements have not been made on any of the in-service bridges.

**Figure 3. Reinforcing bar depth related to the percentage of deterioration.**



Figure 3. Reinforcing bar depth related to the percentage of deterioration.
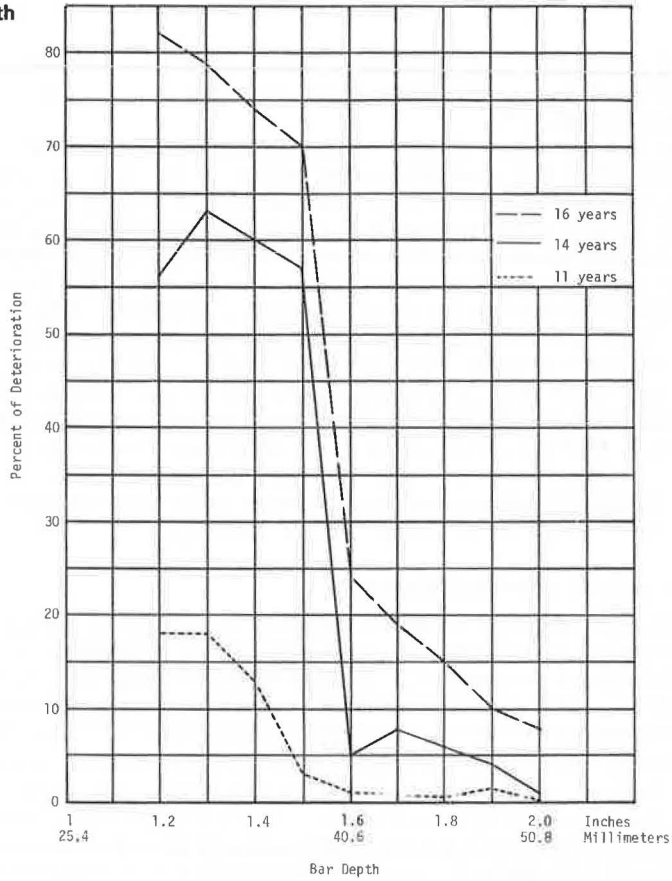
**Table 1. Corrosion potentials of new bridges.**

| Deck Area (ft²) | Observations | Observations Having Midcell Values for Cell Range of 0.1 V (percent) | | | | |
|---|---|---|---|---|---|---|
| | | 0.05 | 0.15 | 0.25 | 0.35 | 0.45 |
| 5,200 | 216 | 29 | 64 | 6 | 1 | 0 |
| 5,320 | 243 | 28 | 63 | 6 | 3 | 0 |
| 5,320 | 252 | 43 | 46 | 6 | 5 | 0 |
| 7,504 | 385 | 96 | 4 | 0 | 0 | 0 |
| 7,504 | 388 | 21 | 71 | 4 | 3 | 1 |
| 14,480 | 656 | 87 | 13 | 0 | 0 | 0 |
| 14,480 | 640 | 80 | 20 | 0 | 0 | 0 |
| 14,680 | 650 | 12 | 88 | 0 | 0 | 0 |
| Total | 3,430 | 49.5 | 46.1 | 2.8 | 1.5 | 0.1 |

Note: 1 ft² = 0.09 m².

**Table 2. Corrosion potentials of in-service bridges in 1973.**

| ID | Deck Area (ft²) | Construction Year | Observations | Observations Having Midcell Values for Cell Range of 0.1 V (percent) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 0.05 | 0.15 | 0.25 | 0.35 | 0.45 |
| 1 | 4,095 | 1958 | 153 | 24 | 53 | 13 | 4 | 6 |
| 2 | 11,950 | 1959 | 644 | 7 | 58 | 8 | 2 | 25 |
| 3 | 6,910 | 1959 | 256 | 0 | 46 | 39 | 10 | 5 |
| 4 | 5,940 | 1960 | 280 | 1 | 21 | 63 | 14 | 2 |
| 5 | 4,920 | 1963 | 217 | 57 | 19 | 11 | 12 | 1 |
| 6 | 6,980 | 1963 | 310 | 90 | 10 | 0 | 0 | 0 |
| 7 | 8,935 | 1963 | 417 | 49 | 33 | 6 | 6 | 6 |
| 8 | 9,610 | 1964 | 423 | 30 | 56 | 10 | 3 | 1 |
| 9 | 5,000 | 1964 | 232 | 36 | 60 | 4 | 0 | 0 |
| 10 | 4,500 | 1965 | 201 | 22 | 48 | 18 | 10 | 2 |
| 11 | 6,912 | 1965 | 314 | 46 | 47 | 7 | 0 | 0 |
| 12 | 14,100 | 1968 | 398 | 36 | 46 | 15 | 2 | 1 |
| 13 | 7,820 | 1968 | 332 | 24 | 66 | 7 | 3 | 0 |
| 14 | 9,135 | 1969 | 375 | 99 | 1 | 0 | 0 | 0 |
| 15 | 6,370 | 1970 | 292 | 50 | 45 | 5 | 0 | 0 |
| Total | | | 4,844 | 38.1 | 40.6 | 13.7 | 4.4 | 3.2 |

Note: 1 ft² = 0.09 m².

## Changes in Environment

The change of an anode area to a cathode area of a corrosion cell by repairs or by changing environment has been suggested by Stewart (10). We believe this explains some unusual pH relation that we observed on some reinforcing steel.

On a bridge that had been heavily salted, many delaminated concrete sections formed at the anode portion of the corrosion cells. The delaminated concrete was jackhammered out at the anodes leaving many potholes. A heavy rain filled the potholes with water, which rapidly became highly basic from dissolved calcium hydroxide. At several locations we observed small "blisters" on the corroded reinforcing steel. The blisters formed rapidly enough for their growth to be observed. In studying this phenomenon, we discovered that the pH inside the blister was usually below 3 and often below 1. The pH of the water outside the blisters but only 1 or 2 mm away usually was 12 or more. Chemical investigations revealed that the low pH liquid inside the blister was hydrochloric acid, apparently formed because of the changed environment.

High pH conditions were created by the rainwater reacting with the cement-paste phase of the concrete around the pothole. This changed the original anode area to a cathode area compared to another nearby spot in the concrete. Hydrogen ions released at the new cathode apparently reacted with chloride ions in the water to form the hydrochloric acid.

The process was repeated with deteriorated concrete and corroded reinforcing steel in laboratory experiments approximating field conditions, and blisters formed. We found that cathodic areas sometimes formed and HCl was produced on the surface of reinforcing steel even when no blister formed. These areas could be located by placing a solution of potassium ferricyanide [$\frac{1}{2}$ gram of $K_3Fe(CN)_6$ dissolved in 100 ml of distilled water] on the reinforcing steel. If hydrochloric acid was present at the surface of the steel, the acid and potassium ferricyanide reacted with the ferrous iron to form Turnbull's blue. If no acid was present, no blue was formed.

Occasionally the environment of a bridge deck is such that different corrosion aspects are observed. On a pair of 14-year-old steel girder bridges, the outermost eighth of the decks were badly deteriorating full depth. The remainder of each deck was in reasonably good condition. Both decks had been covered with a 2-in. (50.8-mm) hot-mixed overlay before traffic was allowed on the bridge because the decks would receive large amounts of de-icing salts. Water seeped completely through the decks where there was full-depth deterioration. A black deposit accumulated on the bottom of each deck alongside the outermost steel girder. The dark material appeared to form above the girder and to be squeezed out to the side of it by live loads on the bridge. X-ray diffraction studies showed that the black substance was magnetic iron oxide identical to the natural mineral magnetite ($Fe_3O_4$). We thought that it was being derived from the reinforcing steel in the deteriorating concrete.

The following year the deteriorated concrete was all removed, and a new section cast in its place. We were surprised to find the reinforcing steel with little rust. The magnetic iron oxide formed from corrosion of the top of the steel girders where there was considerable corrosion pitting. In this instance, it appeared that the steel girder acted as a sacrifical anode protecting the reinforcing steel from corrosion even in the presence of seeping saltwater. In spite of the fact that the reinforcing steel had very little corrosion, the concrete was deteriorating full depth, but it was still in place.

## Aggregates and Corrosion

Alkali reactive aggregates have been responsible for the formation of small hollow planes above the reinforcing steel (7). When these are near enough to the surface of the deck, they create pop-outs that act as an entranceway for salty meltwater to flow into the hollow plane and carry chlorides close to the reinforcing steel (5). This process speeds the time to corrosion. One means of reducing aggregate reactivity is to use low alkali cement; this has been used in Kansas as in many other states with alkali reactive aggregates. However, alkalies are a corrosion inhibitor (4), and we may be contributing to our corrosion problem in another way by reducing the alkalies in cement to solve our reactive aggregate problem. Whether high alkali or low, the problems seem to persist either way.

Suggestions have been made that some aggregates may affect corrosion. Studies were conducted in our laboratory to determine the corrosion activity of reinforcing steel under conditions of high, medium, and low pH in the presence of carbonate aggregates from different geologic units. The corrosion activity was determined by observing rust formation and by measuring the differential voltage between 2 reinforcing bars of each cell.

Each cell consisted of 2 No. 4 bars separated by $2\frac{3}{8}$ in. (60.3 mm) in a 600-ml beaker. The bar ends that were in the cell were insulated so that corrosion would take place only on the bar perimeter. The different aggregates were placed to a depth of 3 in. (76.2 mm) and then covered with the preselected pH solutions.

The pH of the cells originally were 12.2, 5.7, and 4.4. A gel-like rust formed in the higher pH (12.2) cells first. All cells eventually formed the gel-like rust, which eventually permeated the cell liquid and the aggregate. Electrical potential measurements of the cells were not significantly different. At the end of the test (166 hours), the pH of all the cells were in the range of 6.9 to 8 no matter what the beginning pH. No apparent difference in corrosion due to the aggregate was noted.

## CORROSION OF STRUCTURAL STEEL

The major problem and expense involved with structural steel has thus far been repainting to prevent extensive corrosion. This is costly and a nuisance, yet we must keep corrosion under control. We have tried various kinds of paints, primers, and preparation methods. The end result always seems to point to the same general conclusion: The success and longevity of the paint were usually more dependent on the quality of the preparation, inspection, and application techniques than on the materials used. The quality of the paint has been controlled well enough, but shortcuts in preparation or lackadaisical inspection have sometimes contributed to a poor final performance. Several years ago we changed our preparation requirements from wire-brushing to sandblasting techniques, and that has been beneficial.

Corrosion begins on some steel girders quite early. It starts in the area below the scuppers where de-icing salts flow through the deck drains and fall onto the bottom flanges of the outer girder. A plastic extension on the cast-iron deck drains to carry the saltwater below the girders before it drops should do much for the longevity of the paint and help prevent rusting of the structural steel.

## SUMMARY OF OBSERVATIONS

Bridge deck corrosion has increased in Kansas as the use of de-icing salts has increased. Spalls and hollow planes develop in concrete bridge decks as a result of corrosion. Reactive aggregate particles also create hollow planes and pop-outs that allow de-icing saltwater to come in close proximity to the reinforcing steel.

The copper-copper sulfate half-cell method, if properly used and intelligently interpreted, will reveal areas of corroding reinforcing steel. This method was used to locate corroding steel in a bridge that had no detectable hollow planes or spalls. About a year later both types of damage were found in the area of active corrosion. Some new bridges that have shown a small percentage of readings in the active corrosion range will be monitored through the coming years.

Steel girders seem to serve as sacrificial anodes in unusual situations. Magnetite formed as a product of the girder corrosion, but the reinforcing steel was protected from corrosion even though the concrete deteriorated to the extent that it had to be removed and replaced.

Very low pH spots found on reinforcing steel during repair operations were determined to be hydrochloric acid that was formed as a result of a change in environment, which caused an anode area of a corrosion cell to change to a cathode. Hydrogen ions released at the cathode apparently reacted with chloride ions from the salt-contaminated concrete to form the hydrochloric acid.

Concrete deterioration associated with the corrosion of reinforcing steel can be reduced or delayed by increasing the depth of cover over the top reinforcement and by improving the quality of the concrete. Structural steel corrosion can be reduced by proper

preparation and quality inspection during painting operations. Keeping salty meltwater away from the painted steel also helps.

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