

**MICHIGAN DEPARTMENT OF TRANSPORTATION
M•DOT**

**INVESTIGATION OF CONDITION OF PRESTRESSED
CONCRETE BRIDGES IN MICHIGAN**

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Introduction

Prior to the 1950s, in Michigan, two major types of bridges were built; steel and reinforced concrete. Steel beams were used more than reinforced concrete because they provided longer, more efficient spans. Of the 4,138 bridges built prior to 1950, the breakdown consisted of 2,468 steel (60 percent) and 1,670 (40 percent) reinforced concrete.

In 1954, prestressed concrete was introduced to Michigan. This bridge type quickly became popular, because the beams could be built economically in plants and their span lengths could compete with that of steel beams. Prestressed beams have proven to be economical since up to now they have been virtually maintenance free, unlike steel beams that require costly sandblasting and painting. For these reasons, each year the State of Michigan has increasingly used more prestressed beams. Today, prestressed beam bridges are a substantial percentage of Michigan's bridges. Table 1 shows the number of prestressed beams and the percentage of Michigan's (state and local agencies) total bridge population per decade according to data from the Michigan Department of Transportation's (MDOT) Bridge Management Unit.

In 1996, Michigan has 1,696 prestressed box beams and 696 prestressed I-beam structures. MDOT has 717 prestressed bridges in service on the trunklines, 157 of the box beam and 560 of the I-beam structures. The local government agencies are responsible for the remaining 1,675.

Because many of Michigan's prestressed beams are nearing 50 years old, this study was initiated to investigate the condition and study potential maintenance problems of prestressed beam structures.

Reviewing the bridge inventory files, we discovered that as of April 5, 1996, 98 percent of Michigan's (state and local agencies) prestressed concrete bridges had a superstructure rating of five and higher. The superstructure condition is rated by the Maintenance Division. The files are maintained by the Bridge Management Unit of MDOT. A rating of five indicates the superstructure is in "fair" condition. Eighty-eight percent of Michigan's (state and local agencies) prestressed bridge superstructures were rated, seven or better. Figure 1 displays the superstructure rating of Michigan's (state and local agencies) prestressed concrete bridges as a pie chart, and Table 2 displays the condition rating scale.

To fully understand the condition of Michigan's prestressed bridges, a review of prestressed I-beams and box beams, in their perspective jurisdiction, was conducted. The review revealed the results displayed in Figure 1 through 5. Eighty-three percent of Michigan's trunkline box beam bridges, along with 72 percent of I-beam bridges are rated seven or higher. Ninety-nine percent of the local agencies box beam bridges, along with 91 percent of I-beam bridges, are rated seven or higher.

We also compared the superstructure ratings of prestressed beam structures with that of steel bridges (built after 1950). Figures 6-8 display the comparison between the superstructure ratings. These graphs are used to show the differences between MDOT, local agencies and all Michigan bridges. The superstructure condition of the prestressed beam bridges are outperforming the steel beam bridges. When comparing the superstructure ratings of bridges located on MDOT's trunklines, 81 percent of the prestressed concrete beam bridges are rated seven or higher, compared to only 60 percent of the steel beam bridges. Comparing the superstructure ratings of the structures located on local agency roadways, 91 percent of the prestressed beam bridges are rated seven or higher with only 69 percent for the steel beam bridges. For all of the bridges located throughout the state of Michigan (MDOT and local agencies), 88 percent of the prestressed beam bridges are rated seven or higher, compared to 61 percent of the steel beam bridges.

One major concern bridge engineers have when examining prestressed beams is the corrosion of prestressing strands. Steel's corrosion product can be two times greater than the original steel, creating very high internal pressure. Pressures of this magnitude are far greater than the tensile strength of concrete, resulting in spalls and delaminations to the surrounding concrete. Since prestressing strands are stressed to very high levels and have a smaller diameter than rebar, the fear is corrosion will affect the load carrying capacity of a prestressing strand to a greater degree than rebar in conventional reinforced concrete in a similar environment.

Methodology

It is important to determine the effects of corrosion on prestressed strands. Reinforcing steel embedded in concrete has a cover of iron oxide film, a natural protective coating, created during the curing process of the concrete. The film is generated due to the high alkaline environment caused by the hydration of Portland cement. During winter months, road salt is used to maintain the roadways. When chloride (road salt) is introduced into concrete, the natural protective coating will eventually become unstable. Presence of chloride decreases the pH level in the concrete, thus disrupting the oxide film. When oxygen, water, and chloride combine and contact the unprotected strands, the environment for corrosion is initiated.

To determine the susceptibility of prestressed beams to corrosion and to study the effects of corrosion on the strands, our investigations was divided into two stages.

In Stage 1 we took chloride samples from twelve bridges, seven box beam structures and five I-beam structures. Our objective was to determine if the chloride concentrations in a representative number of typical prestressed beams is theoretically high enough to initiate corrosion in the beams.

The box beams studied are as follows:

- Raymond Road over Pine River (B01 of 43-06-21)
- Prairie Road over Pine River (B01 of 56-4-14)
- Route 593 over Torch River (B01 of 5-12-21)
- Shepardsville Road over Maple River (B02 of 19-6-25)
- I-94 over New York Central Railroad (R01 of 11016 WB and EB)
- US-27 over Pennsylvania Central Railroad (R01 of 23061)

The five I-beam structures are as follows:

- River Road over US-23 (S01 of 72014)
- US-27 over M-17 (S02 of 81074)
- Pembroke over M-39 (S09 of 82193)
- 102nd St. over US-131 (S01 of 03111)
- I-96 over Washington Avenue (S02 of 33083)

In Stage 2, we visually inspected and tested steel strands removed from four structures and took chloride samples next to the strands. Stage two was done to try to make a correlation between the chloride content in the concrete and the remaining ultimate strength of the strands.

The four structures studied were:

- Hawkins Road over I-94 (S11 of 38101)
- Oxford Street over C&D Railroad (R01 of 41-25-46)
- 20th Street over Kalamazoo River (B01 of 13-04-31)
- Hotchkiss Road over M-47 (S01 of 09091)

Stage 1

This stage was executed during the summer of 1989-1990. A literature search was conducted to determine the amount of chloride required in reinforced concrete to initiate corrosion. Eight different sources were used and the search yielded a contamination threshold of 0.78 kg of acid soluble chloride per cubic meter of concrete required to initiate corrosion, which exclude any chloride contribution from the aggregate (background chlorides). Any background chlorides from the aggregate would increase the threshold value. Table 3 displays the sources and values found. If the chloride content falls below the threshold, chloride contamination is not a concern. When chloride content exceeds the threshold, the concrete is considered contaminated and corrosion is possible.

Deicing salt is not the first introduction of chlorides into concrete. The first chlorides are introduced by the aggregate. Natural aggregates have a chloride content that contributes to the overall concrete chloride level, but not necessarily to the contamination level. This is referred to as background chloride. To determine the

background chloride of aggregates used by the State of Michigan we conducted a search of the current aggregate sources used in prestressed concrete. The Materials and Technology Division's Aggregate Quality Control Group records reveal that out of 21 sources used for prestressed beams, the aggregate chloride content ranged from 0.12 kg per cubic meter to 5.06 kg per cubic meter. The average was 2.56 kg per cubic meter, with a standard deviation of 1.34. It is unknown how much the background chlorides contribute to the overall chloride content of the concrete, yet there exists a potential for background chlorides higher than the threshold of 0.78 kg per cubic meter even before the concrete is placed.

Concrete powder samples were extracted from the 12 structures studied at the prestressed strand depths using a hammer drill with a 19 mm diameter bit. The specific location of each sample was determined through plan reviews. For comparison, samples were taken from visually sound concrete and obvious delaminated and rust stained areas caused by steel corrosion. This sampling method holds true for both the prestressed box beams and the prestressed I-beams. The chloride content was determined through chemical analysis. Acid soluble tests were used to determine the kilograms per cubic meter of chloride in the concrete in all but one case.

One problem encountered during the field inspection was limited accessibility to the bottom of the structures over rivers. Although a boat was used, a close inspection of the beams was often not possible. Concrete samples for chloride analysis were not obtained from portions of the structure that were directly over water.

Box Beam Structures:

The following prestressed box beam structures were selected for detailed inspection.

1. Raymond Road over Pine River near Alden (B01 of 43-06-21)
2. Prairie Road over Pine River near Midland (B01 of 56-4-14)
3. Route 593 over Torch River near Kalkaska (B01 of 5-12-21)
4. Shepardville Road over the Maple River near St. Johns (B02 of 19-6-25)
5. I-94 WB over New York Central Railroad near Benton Harbor (R01 of 11016)
6. I-94 EB over New York Central Railroad near Benton Harbor (R01 of 11016)
7. US-27 over Pennsylvania Central Railroad near Charlotte (R01 of 23061)

All of the prestressed box beams were cast at Lamar Corporation Plant in Grand Rapids, Michigan. The aggregates used for the concrete box beams came from Inland Lime and Stone (Pit 75-5) in Schoolcraft County or Drummond Dolomite Limestone (Pit 17-40 or 17-66).

All of the studied box beams were constructed between the years 1960 and 1971, and had 10 mm seven wire prestressed strands. The strand's ultimate strength varied from 89 kN for Grade 250 steel, prior to 1962, and 102 kN for Grade 270 steel after 1962. The minimum concrete compressive strength ($f'c$) was required to be 34 MPa. The following sections describe each bridge and show the chloride test results.

During the concrete powder analysis, certain samples yielded much higher chloride content values than the average. These high values skewed the results when compared with the majority of the chloride content values. Therefore, we decided to perform a T "one-sided test" in accordance with ASTM E178-94 "Standard Practice for Dealing with Outlying Observations" (11). Some of the high chloride values were deemed outliers and were not used for statistical calculations or comparison in this report. Because we cannot determine if the outliers are totally irrelevant, we have included them in this report in Table 4. The remaining chloride data are summarized in Table 5.

Raymond Road over Pine River (B01 of 43-06-21)

The box beam structure was built in 1971. It is located 4.83 km south of Bristol Road in Ellsworth Township, Lake County. At the time of the study, the structure had an ADT count of 300 vehicles, and the superstructure was rated at nine (refer to Table 2 for rating).

The Raymond Road structure consists of two identical spans, 18.3 m in length. The bridge (Figure 9) provides a clear roadway width of 11.1 m. The superstructure consists of simply supported, precast, prestressed concrete box beams, 914 mm wide and 381 mm deep. The fascia beams are identical to the interior beams, except for an outside flange edge 38 mm deeper and 76 mm wider. Each beam contains twenty-eight 10-mm diameter, seven wire prestress steel strands. An asphalt wearing course had been applied to the top of the structure.

The fixed joints over the abutments were in better condition than the expansion joints over the piers. Medium leakage of water and small concrete spalls were observed at the piers. No deterioration was observed on the beams. All of the beams (Figure 10) were in excellent condition. Only slight rust stains were observed at the soffit. The existing bridge deck had a bituminous overlay, which was in good condition. Extensive cracks in the overlay were observed over the piers and the abutments.

We used this structure as a baseline for comparing bridges with greater deterioration, since the superstructure was rated at nine, representing a superstructure in excellent condition. Studying this bridge provided a better understanding of chloride content in a bridge that is in excellent visual condition.

The results of our study are shown in Figure 11 as a histogram displaying the number of occurrences at each chloride level. These data are analyzed further in

Table 5, which shows the average chloride level for the bridge along with the average chloride levels at the piers, abutments and interior spans. From the 90 extracted concrete powder samples, 0.0 percent fell above the corrosion threshold limit. This correlates with the superstructure rating of nine.

Prairie Road over Pine River (B01 of 56-4-14)

The existing box beam structure, built in 1970, is located 1.61 km south of M-20 and 3.63 km west of Midland in Homer Township, Midland County. At the time of the study, the structure had an ADT count of 1,150 vehicles and the superstructure was rated at seven.

The Prairie Road structure (Figure 12) consists of three identical spans, 18.3 m in length. The bridge provides a clear roadway width of 11.1 m. The superstructure consists of 12 simply supported, precast, prestressed concrete box beams, 914 mm wide and 381 mm deep. The fascia beams are identical to the interior beams, except for 38 mm thicker flange on the outside edge. Each beam has thirty-one 10-mm diameter, seven wire prestress steel strands. An asphalt wearing course (Figure 13) has been applied to the top of the structure. Expansion joints are over the piers and fixed joints are over the abutments.

Since the structure is over a river, accessibility to the underside of the beams was very limited. Span two was completely inaccessible. Spans one and three were accessible near the abutments. All inaccessible areas were visually inspected from a distance and any observed deficiencies were noted.

During our inspection we found extensive rust and water stains on the piers and abutments (Figure 14); no concrete spalls or delaminations were found on the piers or abutments; the bridge deck was overlaid with asphalt and was, generally, cracked over the piers and abutments; water leakage was limited to the beam ends.

The results of our study are shown in Figure 15 as a histogram displaying the number of occurrences at each chloride level. This data is analyzed further in Table 5, which shows the average chloride level for the bridge, along with the average chloride levels at the piers, abutments and interior spans. From the 41 extracted concrete powder samples, 36.6 percent fell above the corrosion threshold limit. This could correlate with the superstructure rating of seven.

Route 593 over Torch River (B01 of 5-12-21)

The existing box beam structure was built in 1971 and is located in Antrim County. At the time of the study, the structure had an ADT count of 2,040 vehicles and the superstructure was rated at five.

The existing structure consists of three spans. Spans one and three are identical and have a span of 12.2 m. Span two, shown in Figure 16, is 18.3 m long. The

bridge provides a clear roadway width of 7.9 m. The superstructure consists of simply supported, precast, prestressed concrete box beams. The beams in span one and three are 914 mm wide and 533 mm deep that include nineteen 10-mm diameter, prestress strands. Figure 17 shows a technician collecting a concrete powder sample from the bottom of a beam in span three. The beams in span two are 914 mm wide and 686 mm deep and include thirty-four, 10 mm diameter, steel strands. An asphalt wearing course has been applied to the top of the structure.

During the inspection of B01 of 5-12-21, we discovered; cracks in the box beams were centralized at beam ends; the bridge deck had extensive transverse cracks over the piers and the abutments with more rust stains at the piers; and the deck also had extensive longitudinal cracks between adjacent box beams.

The chloride content results of our study are shown in Figure 18 as a histogram displaying the number of occurrences at each chloride level. These data are analyzed further in Table 5, which shows the average chloride level for the bridge along with the average chloride levels at the piers, abutments and interior spans. From the 180 extracted concrete powder samples, 0.0 percent fell above the corrosion threshold limit. This does not correlate with the superstructure rating of five.

Shepardsville Road over Maple River (B02 of 19-6-25)

The existing box beam structure is located 7.24 km north of Shepardsville in Duplain Township, Clinton County and was built in 1971. At the time of the study, the structure had an ADT count of 1,207 vehicles and the superstructure was rated at five.

The Shepardsville structure consists of three identical spans, 16.2 m in length. The bridge provides a clear roadway width of 9.1 m. The superstructure consists of simply supported, precast, prestressed concrete box beams, 914 mm wide and 533 mm deep. Each beam has twenty-five 10-mm diameter, seven wire prestress steel strands. An asphalt wearing course has been applied to the top of the structure.

Our inspection confirmed that the Shepardsville structure was in fair condition. No spalls, cracks, or delaminations were observed on the box beams although rust and water stains were observed at the beam ends. The expansion joints were providing inadequate protection against water leakage. Extensive cracking of the bituminous overlay, shown in Figure 19, was observed near the construction and expansion joints along with longitudinal cracks between the adjoining beams. Water stains on the abutment wall can be seen in Figure 20.

The results of our study are shown in Figure 21 as a histogram displaying the number of occurrences at each chloride level. These data are analyzed further in Table 5, which shows the average chloride level for the bridge along with the average chloride levels at the piers, abutments and interior spans. From the 69 extracted

concrete powder samples, 18.8 percent fell above the corrosion threshold limit. This may correlate with the superstructure rating of five.

I-94 over the New York Central (NYC) Railroad (R01 of 11016 WB & EB)

The existing box beam structure, located in Berrien County, was built in 1960 and widened in 1965 for increased capacity, as shown in Figure 22. At the time of the study, the westbound structure had an ADT count of 7,950 vehicles and a superstructure rating of eight. The eastbound structure had an ADT count of 7,950 vehicles and a superstructure rating of seven.

Both structures consist of three identical spans, 14.2 m in length. The bridges provide a clear roadway width of 15.8 m. The superstructures consists of simply supported, precast, prestressed concrete box beams, 914 mm wide and 533 mm deep. The eastbound fascia beams were added during a widening project. Each beam has thirty-three 10-mm steel strands. An asphalt wearing course has been applied to each structure. Expansion joints are over both piers and abutment A. Abutment B has the location of the fixed joints.

Our inspection revealed the following. The box beams for both R01 of 11016 (WB) and (EB) structures are in good condition. Due to leaky joints, there was deterioration of the concrete at the beam ends. Deterioration at the abutments was comparatively less than at the piers. Water stains were more pronounced at the beam ends than at the interior-spans. Figure 23 shows the joint condition, along with water stains and efflorescence located at the piers of the eastbound structure. The eastbound structure exhibited an unusually wide gap between the south fascia and the first interior beam allowing the penetration of water. A similar gap was observed between the north fascia and the first interior beam of the westbound structure. The condition of the box beams added for the widening were in better condition than the existing beams. Although the bridge deck had a latex modified overlay, extensive map cracking was observed. Longitudinal cracks between adjoining beams are present on both eastbound and westbound bridge decks. Most of these cracks were between the interior beams and the fascia beams. Adjacent beams were bolted together with threaded rod.

The results of our study are shown in Figures 24 and 25 as a histogram displaying the number of occurrences at each chloride level. These data are analyzed further in Table 5, which shows the average chloride level for the bridge along with the average chloride levels at the piers, abutments and interior spans. From the westbound structure we extracted 120 concrete powder samples, 59.2 percent fell above the corrosion threshold limit. This does not correlate with the superstructure rating of eight. From the eastbound structure we extracted 100 concrete powder samples, 70.0 percent fell above the corrosion threshold limit. This does not correlate with the superstructure rating of seven.

US-27 over the Pennsylvania Central Railroad (R01 of 23061)

The existing box beam structure, located in Eaton County, was built in 1960 and later widened to increase the traffic capacity. At the time of the study, the structure had an ADT count of 5,400 vehicles and the superstructure was rated at six.

The structure (Figure 26) consists of three identical spans, 14.1 m in length. The bridge provides a clear roadway width of 16.0 m. The superstructure consists of simply supported, precast, prestressed concrete box beams, 914 mm wide and 686 mm deep. Each beam has twenty-five 10-mm diameter steel strands. The top of the box beam structure was covered with an asphalt wearing course. Expansion joints are over both piers and abutment A. Abutment B has fixed joints.

During our inspection we made the following observations. The overall condition of the superstructure for R01 of 23061 was satisfactory. The extensive water and rust stains, shown in Figure 27, observed on the underside of the beams were not limited to any particular span. Cracks and delaminations were present at the ends and sides of the box beams. Prestressing strands were exposed at specific delaminated locations. The condition of the structure justified extensive chloride sampling. Many samples were taken at locations with cracks, rust and water stains.

The results of our study are shown in Figure 28 as a histogram displaying the number of occurrences at each chloride level. These data are analyzed further in Table 5, which shows the average chloride level for the bridge along with the average chloride levels at the piers, abutments and interior spans. From the 148 extracted concrete powder samples, 36.5 percent fell above the corrosion threshold limit. This could correlate with the superstructure rating of six.

Results - Box Beam Structures

Although the ages of all the structures are similar, the box beam bridges on county roads are in better condition than those on state trunklines. This is expected due to increased traffic loads and chemical deicers applied to the trunklines. The average chloride content on the county structures was 0.42 kg per cubic meter, compared with 0.98 kg per cubic meter on the highway structures. Table 5 displays the average chloride level for each bridge, along with average chloride levels at the piers, abutments, and interior spans.

We observed small diagonal cracks on the beams on all trunkline structures, and one county structure (B01 of 5-12-21). Cracking was localized to areas exposed to drainage, thus resulting in excessive water and rust stains. Although some small cracks were present, they represent no loss to the structural capacity.

Three out of the seven box beam bridges tested displayed an average chloride content higher than the threshold. The three structures exceeding the threshold all support trunkline traffic over railroad tracks and are not subjected to the effects of under spray mist from trunkline traffic under the bridge. Therefore, we feel the chloride contamination is primarily the result of leaky joints and filtration through

the deck. Chloride values for the interior span and support areas all exceed the threshold limit.

During our visual inspections, we found the ends of the box beams exhibited greater deterioration than the interior areas. The greater deterioration at the ends of the beams may be due to salt-laden water leaking from the joints over the supports. Since most of the joints above the box beams leak, one could assume higher chloride content was present near the supports. An examination of our chloride sampling shows, for all seven structures, the average chloride content ranged from 0.74 kg per cubic meter near the supports, to 0.65 kg per cubic meter away from the supports. Although the averages display higher chloride content at the support ends, please note that two out of the seven box beam bridges exhibited a larger chloride amount at the interior portion than at the supports. (The interior portion consists of the distance spanning the supports minus 610 mm either side.) Therefore, we feel our data do not show an adequate correlation between visual condition and the chloride content. The assumption that more contamination is present through the joints on a box beam structure, is disproved by one third of the structures measured. Deterioration and water stains do not automatically represent a high chloride contamination.

We could not make a connection between superstructure rating and chloride level. For example, the bridge with the worst superstructure rating had the lowest average chloride content. However, there is a possible connection with chloride content and ADT. The bridges with the higher ADTs also had higher chloride content.

I-beam structures:

The following prestressed I-beam structures were selected for detailed inspection.

1. River Road over US-27 near Houghton Lake (S01 of 72014)
2. US-23 over M-17 in Wastenaw County (S02 of 81074)
3. Pembroke Avenue over M-39 in Detroit (S09 of 82193)
4. 102nd Street over US-131 near Otsego (S01 of 03111)
5. Washington Avenue over I-96 near Lansing (S02 of 33083)

The selection of the I-beam structures was made based on the following criteria:

1. ADT of the Structure - For comparison purposes, the ADT of the selected structures varied from 730 to 25,850 vehicles.
2. Location of the Structure - For comparison purposes, structures were selected in both rural areas and metropolitan areas. The urban structures are believed to be subjected to higher chloride exposure.
3. Age of the Structure - An effort was made to select structures of the same age to eliminate age as a factor.

4. Condition Rating of the Structure - For comparison purposes, structures with the low condition ratings were selected for detailed inspection. The superstructure ratings varied from seven to five. Refer to Table 2 for a description of superstructure ratings.

All of the studied I-beams bridges were all constructed in or after 1962, and consisted of 11 mm, seven wire strands with an ultimate strength of 102 kN. The minimum concrete compressive strength ($f'c$) was 34 MPa psi.

During the concrete powder analysis, certain samples yielded much higher chloride content values than the average. These high values skewed the results when compared with the majority of the chloride content values. Therefore, we decided to perform a T “one-sided test” in accordance with ASTM E178-94 “Standard Practice for Dealing with Outlying Observations” (11). Some of the high chloride values were deemed outliers and were not used for statistical calculations or comparison in this report. Because we cannot determine if the outliers are totally irrelevant, we have included them in this report in Table 6. However, from the deemed outliers, most values excluded were extracted from areas near the piers. This suggests contamination from leaky joints. The remaining chloride data are summarized in Table 7.

River Road over US-27 (S01 of 72014)

This existing I-beam structure, located in Roscommon County, was constructed in 1967 and when studied had an ADT of 730 vehicles with a superstructure rating of five.

The structure (Figure 29) consists of four spans. Spans one and four are 9.5 m long, and spans two and three are 21.7 m long. Four different I-beam sizes were used. They ranged from 711 mm to 1372 mm in depth. The smallest beams contain 22 strands, and the largest beams contain 60 strands. The clear width roadway is 9.9 m. Expansion joints are located over the piers and fixed joints are located over both abutments. All spans and joints were in fair condition. No spalls or deteriorations of the deck beams were observed.

The results of our study are shown in Figure 30 as a histogram displaying the number of occurrences at each chloride level. These data are analyzed further in Table 7, which shows the average chloride level for the bridge along with the average chloride levels at the piers, abutments and interior spans. From the 75 extracted concrete powder samples, 9.3 percent fell above the corrosion threshold limit. This does not correlate with the superstructure rating of five.

US-23 over M-17 (S02 of 81074)

This existing I-beam structure, located in Wastenaw County, was constructed in 1962. At the time of the study, the ADT of the structure was 25,850 vehicles and the superstructure rating was seven.

The structure consists of four spans. As shown in Figure 31, spans one and four are 11.5 m, and spans two and three are 16.3 m in length. Two different beam sizes were used for the structure. All of the beams in span two and three, along with the fascia beam for spans one and four, are 1143 mm deep. The interior beams have 32 strands and the fascia beams have 10 strands. The depth for the interior beams in spans one and four is 914 mm. Span one includes 18 strands, and span four consists of 16 strands. All joints located over the piers and abutments are expansion.

Water was observed leaking from the expansion joints, causing more deterioration at the beam ends found over the piers than at the abutments. In Figure 32, we found efflorescence on pier 3. Concrete spalls were only visible at the beam ends.

The results of our study are shown in Figure 33 as a histogram displaying the number of occurrences at each chloride level. These data are analyzed further in Table 7, which shows the average chloride level for the bridge along with the average chloride levels at the piers, abutments and interior spans. From the 121 extracted concrete powder samples, 23.1 percent fell above the corrosion threshold limit. This could correlate with the superstructure rating of seven.

Pembroke Avenue over M-39 (S09 of 82193)

This existing I-beam structure, located in Wayne County, was constructed in 1962 and when studied had an ADT of 4,830 vehicles. The superstructure rating, when studied, was six.

The structure consists of two, 15.8 m, equal span lengths (Figure 34). The clear roadway width is 9.1 m. One size I-beam, 914 mm in depth, was used for the structure. The beam included 28 prestressed strands. Fixed joints are located at the abutments and expansion joints are located at the pier.

Efflorescence was observed on the underside of the beams (Figure 35). No notable cracks or delaminations were observed. These I-beams were in good condition.

The results of our study are shown in Figure 36 as a histogram displaying the number of occurrences at each chloride level. This data is analyzed further in Table 7, which shows the average chloride level for the bridge along with the average chloride levels at the piers, abutments and interior spans. From the 94 extracted concrete powder samples, 12.8 percent fell above the corrosion threshold limit. This could correlate with the superstructure rating of six.

102nd Street over US-131 (S01 of 03111)

This existing I-beam structure, located in Allegan County, was built in 1962. When studied, the ADT was 910 vehicles and the condition of the superstructure was seven.

The structure has four spans. Three sizes of I-beams were used in the construction of S01 of 03111. The sizes of the beams were 711 mm, 914 mm, and 1143 mm in depth. The strands in each respective beam are 20, 26, and 44. Spans one and four (Figure 37) are equal in length, 10.5 m long, and spans two and three are equal in length, 21.5 m long. The clear width for the roadway is 7.7 m. Expansion joints are located over the piers, and fixed joints are located over both abutments.

Only slight rust stains were noticed on the I-beams (Figure 38). Generally, they were in good condition, although some hairline cracks were observed.

The results of our study are shown in Figure 39 as a histogram displaying the number of occurrences at each chloride level. These data are analyzed further in Table 7, which shows the average chloride level for the bridge along with the average chloride levels at the piers, abutments and interior spans. From the 73 extracted concrete powder samples, 82.2 percent fell above the corrosion threshold limit. This could correlate with the superstructure rating of seven.

I-96 over Washington Avenue (S02 of 33083)

This existing I-beam structure was built in 1962 and is located in Ingham County. At the time of the study, the superstructure rating was seven and the ADT was 16,700 vehicles.

The structure consists of three spans. Span one and three are 10.2 m long and span two is 12.4 m long (Figure 40). Four different I-beam sizes were used for the structure. They ranged from 711 mm to 1372 mm in depth. The smallest beams contain 22 strands, and the largest beam contains 60 strands. The clear width roadway is 11.4 m. Expansion joints are located over the piers, and fixed joints are located over both abutments.

The I-beam structure was in good condition. Slight discoloration was noticed on the underside of the beams (Figure 41). No spalls or delaminations were observed, although the beam ends were more discolored than the interior-span portions.

The results of our study are shown in Figure 42 as a histogram displaying the number of occurrences at each chloride level. This data is analyzed further in Table 7, which shows the average chloride level for the bridge along with the average chloride levels at the piers, abutments and interior spans. From the 58 extracted

concrete powder samples, 0.0 percent fell above the corrosion threshold limit. This could not correlate with the superstructure rating of seven.

Results- I-Beam Structures

The average chloride content level for the I-beam structures was 0.63 kg per cubic meter. Out of the five bridges studied, one exceeded the threshold of 0.78 kg per cubic meter. Table 7 displays the information gathered from each sampled I-beam. We are uncertain if the chloride content obtained from powder samples can be related to the superstructures' condition.

The bearing areas on the I-beams exhibited larger chloride contamination than the interior areas. When compared to the box beam structures, the I-beam structures appeared in better condition with less deterioration of the bridge decks and beams. With the deck being of sound condition, the joint locations are the only access for water to run across the beam. Although spray mist under the deck likely affected the beams, no comparison could be made with other I-beam bridges to determine the extent of this effect. All of the structures sampled for the I-beam bridges were grade separations over traffic.

Stage 2

The purpose of Stage 2 was to visually inspect and test salvaged prestressed strands for condition and ultimate tensile capacity, along with determining the chloride content of the surrounding concrete. Strand samples were extracted from salvaged prestressed beams and prepared for tensile tests. Samples were taken from various locations along the prestressed strand and tested for ultimate strength. The following are the four structures where strands were removed and destructively tested:

Box Beams

1. Hawkins Road bridge over I-94 near Jackson (S11 of 38101)
2. Oxford Street over C&O Railroad in Grand Rapids (R01 of 41-25-46)
3. 20th Street over the Kalamazoo River in Calhoun County (B01 of 13-04-31)

I-Beams

4. Hotchkiss Road over M-47 in Saginaw (S01 of 09091)

Hawkins Road over I-94 (S11 of 38101)

This bridge located in Jackson County has four spans and a clear roadway width of 7.9 m. Spans one and four are 10.2 m long, and spans two and three are 14.8 m long (Figure 43). The expansion joints are located over piers one and three. Both of the abutments, along with pier two, have fixed joints. The bridge was built in 1957.

The fascia and first interior beams were replaced in 1982. The beams we tested were built in 1982. When studied, the ADT was 2,650 vehicles and the condition of the superstructure was five.

This structure was chosen because the fascia and first interior beams had been repeatedly struck by high loads and required replacement, thus providing a beam we could dissect and destructively test the prestressed strands. Figure 44 shows the efflorescence located on the box beams. When the beams were removed, we extracted fifteen 10-mm strands and 35 concrete powder samples. The strands not damaged by the high load hits were tested for ultimate strength.

Tensile test results, along with a visual rating of the strand's condition, are displayed in Table 8. The average ultimate strength of the tested 10-mm, Grade 250 strands is 90.0 kN, although one of the tested strands, which had severe corrosion, failed to meet the required ultimate tensile load of 88.9 kN. Figure 45 represents the chloride content (average 0.14 kg per cubic meter) found through chemical analysis. From the 35 extracted concrete powder samples, 0.0 percent fell above the corrosion threshold limit. This does not correlate with the superstructure rating of five.

Oxford Street over C&O Railroad (R01 of 41-25-46)

This structure, located in City of Grand Rapids, was reconstructed in 1986. The replaced bridge was a three span prestressed concrete box beam structure with 686 mm deep beams (Figure 46). Spans one and three were 10.0 m long, and span two was 17.4 m long. The clear roadway width was 11.0 m, with 1.8 m sidewalks on both sides. Expansion joints were located over both piers. Fixed joints were located over both abutments.

We examined this structure because the superstructure was in very poor condition and being replaced. The contractor extracted four 10-mm, Grade 250 strands from the replaced beams, which we tested for ultimate strength. Concrete samples were not taken, therefore, the chloride content was not determined. The tensile test results are displayed in Table 9. The only strand that broke below the required strength of 88.9 kN showed slight signs of corrosion.

20th Street over Kalamazoo River (B01 of 13-04-31)

This structure (Figure 47), located in City of Battle Creek, was widened in 1985. During the widening, two beams were removed due to damage caused by a high load hit (Figure 48). The current clear roadway width is 12.2 m, with a total width of 17.8 m. This bridge has eight identical spans of 10.9 m. There are eighteen, 533 mm deep prestressed concrete box beams. Expansion joints are located over piers 1, 3, 5, and 7. Fixed joints are located over piers 2, 4, 6, and both abutments.

We had an opportunity to examine this structure because two beams were being replaced due to damage caused by a high load hit. Twenty-four 10-mm, Grade 250 prestressing strands and 53 concrete powder samples were removed for testing.

Although some of the removed beam strands had moderate corrosion, we noticed the overall underside of the bridge deck was in good condition (Figure 49). The removed beams were damaged and were not representative for the majority of the beams on this structure. The existing fascia beam, shown in Figure 50, has been in service for 11 years and shows no signs of strand corrosion due to the lack of spalls.

Of the 23 strands removed, seven were not included in the results. Three strands were severely corroded and contained broken strands prior to testing. The three excluded strands were 33B (5 out of 7 strands were broken prior to testing), strand 38B (3 out of 7 strands were broken prior to testing), and strand 68A (5 out of 7 strands were broken prior to testing). The strands may have been broken from the high load hit and/or removal from the beam.

The other four strands (5A, 15A, 48A, and 49A) were not included due to unexplainable data, and are shown in Table 10. Although all four strands appeared to have little to no corrosion, they all broke well below the specification limit of 88.9 kN. Possible explanations are errors in testing, flaws/nicks in the strands, or internal corrosion. Internal corrosion is corrosion on the surface of strand wire not visible without dismantling the strand, i.e. surface of the wire wrapped within the strand. All of the strands were extracted from the transfer length portion of the prestressed beam, where the stress in the strands is reduced. According to AASHTO (9) section 9.20.2.4 (9), “the prestressing force may be assumed to vary linearly from zero at the end of the tendon to a maximum at a distance from the end of the tendon equal to the transfer length, assumed to be 50 times the strands diameter.” When tensioned and untensioned strands are compared in similar NaCl environments for corrosion, tensioned strands perform markedly better with respect to both corrosion losses and ultimate strength losses than untensioned strands (10). Although the samples extracted from the transfer length region appeared to have little corrosion. The low breaking loads did not relate to the low degree of visual corrosion. Internal corrosion may have been greater than could have been visually noted. The four separated samples had an average breaking load of 49.0 kN. The remaining 16 strand test results are summarized in Table 11.

Concrete powder samples were analyzed for chloride content. The chloride content averaged 2.47 kg per cubic meter (Figure 51), which exceeds the threshold 0.78 kg per cubic meter. From the 53 extracted concrete powder samples, 98.1 percent fell above the corrosion threshold limit.

Hotchkiss Road over M-47 (S01 of 09091)

This structure was the only I-beam tested in Stage 2. It is located in Saginaw County. The structure consists of four spans. Spans one and four are 9.1 m long, and

spans two and three are 18.4 m long (Figure 52). The clear roadway width is 7.9 m. Expansion joints are located over the piers and the fixed joints are located over both abutments. This structure was originally constructed in 1965 and studied in 1988. When studied, the ADT was 260 vehicle and the condition of the superstructure was seven.

One beam from the structure was studied. The beam appeared in good condition with no visible corrosion. Three 13-mm, Grade 250 strands were removed from the studied beam. Figure 53 shows technicians removing the strand samples. This was the only bridge in this report that the chloride content was tested through a water soluble test and not the acid test. Water soluble results typically fall 10 to 15 percent below the results from acid soluble tests. Therefore, we added 15 percent to the water soluble results for comparison purpose. The chloride results are shown in Figure 54 (average 0.07 kg per cubic meter for thirteen samples). The average ultimate strength of the strands is 169.1 kN. The tensile test results are displayed in Table 12. The minimum required ultimate strength for the I-beam strands is 160.0 kN. None of the three strands tested were below the minimum ultimate strength. From the 13 extracted concrete powder samples, 0.0 percent fell above the corrosion threshold limit. This does not correlate with the superstructure rating of seven.

Results of Stage 2

I-Beam

The steel strands removed from a 23-year-old concrete I-beam structure (S01 of 09091) had less corrosion than the strands removed from all box beam structures (12-14 years old). Three 13-mm diameter strands were removed from an I-beam and were found in good condition with only the strand ends corroded. The average chloride content in the tested I-beam was 0.07 kg per cubic meter. The prestressed strands failed at an average tensile strength of 169.1 kN. The minimum tensile strength required was 160.0 kN. None of the tested strands fell below the minimum tensile strength for the I-beam.

Box Beams

Three box beam structures were studied in Stage 2. The results of the ultimate tensile strength test and the average chloride content are found in Table 13. Sixteen strands from the 20th Street over Kalamazoo River bridge (B01 of 13-04-31) were tested for tensile strength. One of 16 tested strands fractured below the required load of (88.9 kN), and the average chloride content of the surrounding concrete was 2.47 kg per cubic meter. Hawkins Road over I-94 (S11 of 38101) was in fair condition when tested. The average chloride content was 0.14 kg per cubic meter with only one out of the fifteen tested strands failing the 88.9 kN required tensile strength. The final bridge, Oxford Street over C&D Railroad (R01 of 41-25-46), resulted in one out of four tested strands failing the required tensile strength. The chloride content for this bridge was not determined.

From the data collected, no conclusion can be drawn as to the relationship between the chloride content and the ultimate strength of the prestress strands. Comparing the one available I-beam and the two available box beam studies, a relationship between chloride content and ultimate strength may exist, but there is insufficient information to create a generalized statement. Two of our three bridges studied represent a large ultimate strength with a low chloride content. The low chloride contents are not representative of the chloride samples studied in Stage 1.

Conclusion

According to the status reports of Michigan's Structural Inventory, 88 percent of Michigan's prestressed bridges are rated as "good" condition or better. Superstructure ratings of local agency prestressed bridges are higher than the trunkline. This could be attributed to many factors; traffic volumes, load limits, or salt usage, as well as different inspection procedures. Although prestressed bridges on Michigan's trunklines have lower superstructure ratings than county prestressed bridges, 86 percent are still rated as "fair" or higher condition.

When comparing the superstructure ratings of prestressed beam bridges to that of similar aged steel bridges, the prestressed bridges retain a higher rating than the steel. This implies the prestressed bridges are out performing their steel counterparts.

To determine the chloride level in Michigan's prestressed beams, we extracted concrete powder samples. We found some chloride levels are above the threshold limit, presenting a potential for steel corrosion. However, chloride levels varied randomly throughout the beams. In general, there were no set patterns in relation to sample locations or depths, except for the I-beams where under expansion joints we found elevated chloride levels.

Research and experience has shown chloride contamination of steel rebar and prestressing strands can contribute to accelerated corrosion. From our literature search, we estimate corrosion can initiate in strands when chloride level is greater than 0.78 kg per cubic meter of concrete excluding background chloride from the aggregate. Our study shows we may sometimes have chloride concentrations higher than this and therefore, we may have a potential for prestressing strand corrosion, unfortunately the background chloride is not known with certainty. From our data, we conclude that the chloride content of prestressed concrete is not a good indicator for determining the condition of the prestressed beams due to background chlorides. We tried to find a relation between elevated chloride levels and beam condition. The chloride levels did not relate to our visual inspection of spalled areas, nor to the bridge inspectors' superstructure ratings. One explanation for the seemingly random chloride levels is background chloride is introduced into the concrete powder sample through the aggregate. As the concrete powder samples are extracted from the beams, we cannot distinguish between the cement or aggregates. Therefore, our powder samples may contain aggregates, along with the concrete paste's chlorides content. The average chloride content of the department's 21 aggregate sources used for prestressed concrete ranged from 0.12 kg per cubic meter to 5.06 kg per cubic meter. The average was 2.56 kg per cubic meter with a standard deviation of 1.34. Therefore, even before the concrete is placed, we have the potential of a chloride content higher than our corrosion threshold range of 0.78 kg per cubic meter, and it is believed the background chloride contribution to the corrosion process is minimal.

We also tried to develop a relationship between the concrete's chloride content and the prestressed strand's remaining tensile strength, but with the limited testing we did, we were unable to develop a relationship. We did, however, find severely corroded strands with obvious loss of load carrying capacity and moderately corroded strands with reduced load carrying capacity.

As a result of our study, we conclude the chloride content of prestressed concrete beams is not a good indicator for determining the condition of prestressed beams. We feel visual inspection gives a better representation of the superstructure condition.

Recommendations

Structural Research Unit

1. Due to the unclear nature of low breaking loads for one of the bridges (B01 of 13-04-31) tested in Stage 2, the Structural Research Unit should continue to keep up-to-date with ongoing national research. Currently, the Transportation Research Board is conducting NCHRP project 10-53, "Condition Evaluation of Prestressed Strands in Bridges." This project will detail reliable, cost-effective field methods for evaluating the strength of prestressed beams and aid in the decision making between

bridge rehabilitation versus replacement. We should relate the findings of the NCHRP report and other research projects to Michigan's prestressed bridges.

2. Develop repair procedures for end of prestressed beams damaged by chlorides and/or corrosion.

Maintenance Division

Report deterioration trends in both prestressed box beams and I-beams.

Design Division

Future designs for prestressed bridges should encompass a proper drainage system. If storm water runoff is prevented from coming in direct contact with the beam end, chloride contamination will decrease. Also, designs that eliminate expansion joints should be considered.

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TABLES AND FIGURES